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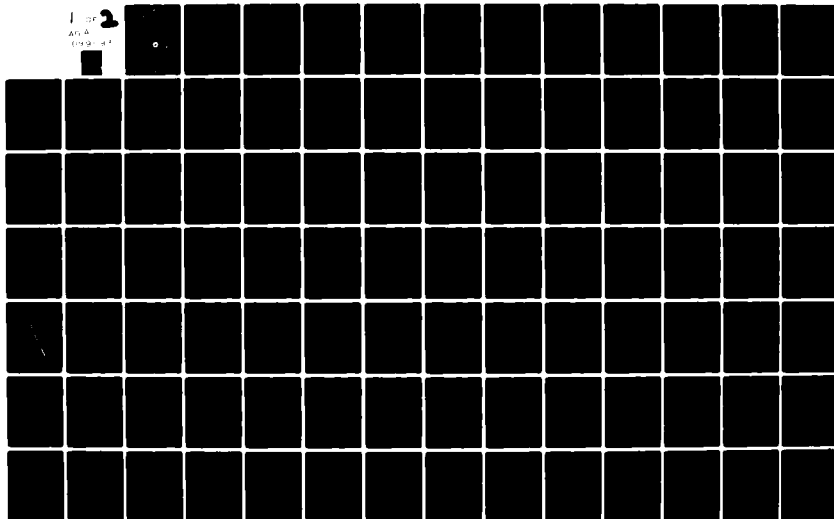
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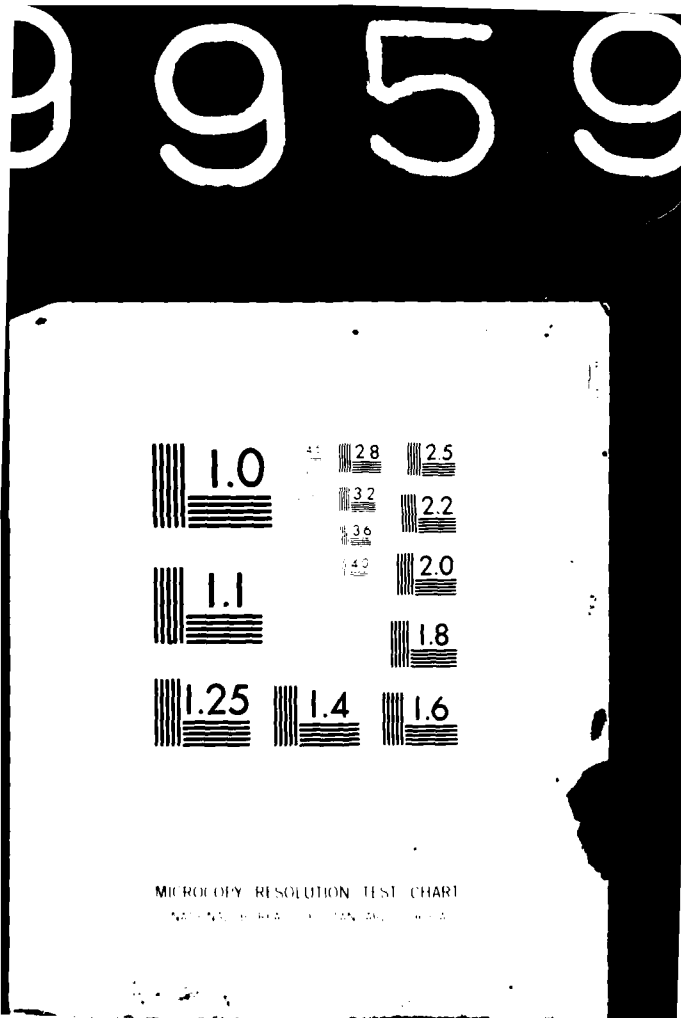
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NONDESTRUCTIVE TESTING FOR LIGHT AIRCRAFT PAVEMENTS

PHASE II

Development Of The Nondestructive Evaluation Methodology

Albert J. Bush III

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Geotechnical Laboratory
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FINAL REPORT

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<p>16. Abstract</p> <p>This study is the second phase of a two-phase program to develop a nondestructive pavement evaluation method to evaluate pavements designed to support aircraft with gross weights of less than 30,000 lb. A methodology that uses the deflection basin from nondestructive testing (NDT) to predict the elastic moduli of up to four pavement layers was developed. A computer program (CHEVDEF) was developed that predicts the moduli so that the deflection basin from a layered elastic solution approximates the measured basin. The nonlinear stress-dependent characteristics of the subgrade are defined. Moduli derived from NDT results are used in the PAVEVAL program developed in an earlier study (FAA-RD-77-186-1) by R. A. Weiss to predict the allowable aircraft loads. The subgrade elastic moduli described by this method compares well with laboratory test results and with results from other methodologies. The predicted allowable load from this method compares well with the allowable load from the dynamic stiffness modulus procedure.</p> <p>Appendix A presents a laboratory procedure for determining the resilient modulus of subgrade soils, Appendix B discusses the CHEVDEF program, and Appendix C presents a guide to the use of the computer program PAVEVAL.</p>			
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METRIC CONVERSION FACTORS

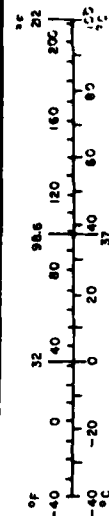
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tabsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.96	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 centimeters. For more exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25. SO Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	1.1	yards	yd
		0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
		1.06	quarts	qt
		0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
		1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This study, the second phase of a two-phase program, was sponsored by the Federal Aviation Administration through Inter-Agency Agreement No. DOT FA78WAI-848, "Nondestructive Testing for Light Aircraft Pavements." Phase I of the study was conducted during the period April 1978 - July 1979 and was reported in FAA Report No. FAA-RD-80-9, "Nondestructive Testing for Light Aircraft Pavements; Phase I, Evaluation of Nondestructive Testing Devices." Phase II was conducted during the period August 1979 - August 1980 under the direction of Mr. J. P. Sale, Chief (retired), Geotechnical Laboratory (GL); Dr. D. C. Banks, Acting Chief, GL; Dr. P. F. Hadala, Assistant Chief, GL; Messrs. R. L. Hutchinson, Chief, Pavement Systems Division (PSD); A. H. Joseph, Acting Chief, PSD; and J. W. Hall, Jr., Chief, Prototype Testing and Evaluation Unit, PSD, of the U. S. Army Engineer Waterways Experiment Station (WES). Dr. Walter R. Barker and Messrs. P. S. McCaffrey, Jr., R. D. Curtis, and A. J. Bush III actively participated in the study. The report was prepared by Mr. Bush.

Director of the WES during the conduct of the investigation and preparation of this report was COL Nelson P. Conover, CE. Technical Director was Mr. Fred R. Brown.

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INTRODUCTION

BACKGROUND

Nondestructive testing (NDT) devices are being widely used to evaluate the load-carrying capability of pavements for air carrier and highway pavements. Evaluation procedures have been developed using various types of NDT devices for these pavements. Phase I¹ of this study evaluated commercially available NDT devices for use on light aircraft pavements (design gross loadings less than 30,000 lb). Phase II, reported herein, is to develop a methodology for evaluation of light aircraft pavements based upon multilayered elastic models and limiting stress/strain criteria.

PURPOSE

The purpose of Phase II of this study is to develop an evaluation procedure based on a multilayered elastic procedure for evaluating pavements that support aircraft with gross weights of less than 30,000 lb. The evaluation will determine the allowable gross aircraft load for a given number of operations.

SCOPE

This study will utilize data only from nondestructive testing devices similar to the Model 2008 Road Rater. Although concepts for the model are general and would probably apply to any of the other devices evaluated in the Phase I study, this device alone was used in development of the evaluation methodology.

DEVELOPMENT OF THE EVALUATION METHODOLOGY

REVIEW OF NDT EVALUATION PROCEDURES

Since a number of NDT pavement evaluation procedures have been developed, a cursory review will be made to outline the confines for which this methodology was restricted.

Green and Hall² reported a procedure that uses the U. S. Army Engineer Waterways Experiment Station (WES) 16-kip vibrator. This procedure uses a dynamic load sweep at a constant frequency of 15 Hz. Only the center deflection is measured and the resultant parameter (dynamic stiffness modulus (DSM)) is computed as the inverse slope of the upper third of the load deflection relationship. The DSM is correlated directly with allowable single-wheel load. The procedure utilizes the U. S. Army Corps of Engineer (CE) California Bearing Ratio (CBR) design for flexible pavements and the Westergaard theory for rigid pavements.

Weiss³ reported a layered elastic evaluation procedure using results from the WES 16-kip vibrator. This procedure is used to predict the subgrade modulus. Since the Model 2008 Road Rater produces a 4000-lb peak load (8000-lb peak to peak) as compared with 15,000-lb peak for the WES 16-kip vibrator, this procedure could not be readily adapted.

Yang⁴ reported a procedure that uses the WES 16-kip vibrator and a frequency sweep where the dynamic load is held constant and the frequency is varied between approximately 5 and 50 Hz. This procedure predicts the subgrade modulus.

The frequency sweep test requires approximately 10 times the amount of time to conduct as a load sweep. WES research indicates that the data derived from a frequency sweep do not warrant the extra time required to collect. Pavement material properties are frequency-dependent. Therefore, another variable is introduced to the evaluation method that must be accounted for.

Treybig et al.⁵ reported a layered elastic evaluation/overlay design procedure using the Dynaflect testing device. In this procedure, the modulus values of the upper layers are assumed. Samples are taken of the granular base and subbase and subgrade materials, which are

tested in the laboratory using a dynamic load triaxial test to determine the resilient modulus. By use of the deflection from the number one sensor of the Dynaflect and assumed or laboratory modulus values, the modulus of the subgrade is determined through a series of nomographs. This modulus is compared with the laboratory results of resilient modulus versus deviator stress. Through a series of approximations of stress and modulus that parallels the laboratory relationship, the design modulus is predicted. The basic concepts of the Treybig procedure are similar to the approach being reported except that a goal in developing this procedure is not to require destructive sampling and laboratory testing.

Koole⁶ reported a layered elastic evaluation/overlay design procedure using the Falling Weight Deflectometer. The deflection at the center of the applied load and the ratio of that deflection to a deflection some distance away from the applied load were used. The pavement was characterized by a three-layer system. The subgrade modulus and either the asphaltic concrete (AC) modulus or the AC thickness are determined in this procedure. The modulus values for the AC layer (if the thickness is to be determined) and layer 2 are determined from laboratory results or from construction records. The effective thickness of the surface layer is determined. From these values, the layered elastic theory is used to predict allowable or overlay requirements.

Anani⁷ reported results using the Model 400 Road Rater. The Model 400 Road Rater, described in detail in Phase 1 of this study, applies a peak-to-peak dynamic load of approximately 720 lb to the pavement through two 4- by 7-in. pads spaced 6 in. apart. Four sensors are used to monitor deflections. One is located between the pads while the other three are spaced at 1-ft intervals.

Anani used the BISAR computer program developed by the Shell Oil Company with successive approximation techniques to determine the elastic moduli of the pavement layers. Using up to a four-layer system, the procedure approximated the E values by the following equation:

$$E(I)_{\text{new}} = E(I)_{\text{old}} \times \frac{RRD(I) + \Delta(I)}{2} RRD(I)$$

where

- $E(I)_{\text{new}}$ = modulus value for layer I
- $E(I)_{\text{old}}$ = previous assumed modulus value for layer I
- $RRD(I)$ = measured deflection corresponding to layer I, i.e., deflection No. 4 is dependent on layer 4 and deflection No. 3 is dependent on layer 3, etc.
- $\Delta(I)$ = deflection from BISAR associated with $E(I)_{\text{old}}$.

Other procedures have been developed by Sharpe⁸ and Ullidtz⁹ that predict modulus values for pavement systems using the layered theory and nondestructive testing devices. These procedures use two deflection measurements from the deflection basin.

As shown above, a number of researchers used nondestructive testing and the layered elastic theory to evaluate and design overlays for pavements. The procedure developed in this study will incorporate some of the stronger points of those procedures as well as add some new approaches.

EXPERIMENTAL DATA

The data used in developing this procedure were collected on the Pennsylvania Transportation Research Facility (PTRF) and on selected pavements at the WES. The PTRF is a one-mile track located at Pennsylvania State University. Fifteen items were tested with the Model 2008 Road Rater in June 1978. From 1 to 20 tests were conducted on each item. The deflections used in this study will be the average of those tests. These averages are given in Table 1 for the 7000- and 5000-lb force levels. The pavement structures of the 15 items are given in Table 2. Also shown in Table 2 are the number of equivalent 18-kip axle loads (EAL) that were applied to the pavement items prior to testing. The surface conditions of the items were good except for items 3, A, and C. These items exhibited some surface distress such as longitudinal and alligator cracking.

Two test pits were excavated in the PTRF to obtain samples of the granular subbase material and the subgrade. Undisturbed block samples and bag (disturbed) samples were taken of the subgrade. Bag samples were also taken of the subbase. Resilient modulus tests were conducted

Table 1
Model 2008 Road Rater Deflections on PTRF Items
for 7000- and 5000-lb Loads

Item	No. of Tests	Mean Pavement Temperature, °F	7000-lb Load				5000-lb Load			
			Mean Peak-Peak Force, lb	Mean Deflection, mills			Mean Peak-Peak Force, lb	Mean Deflection, mills		
				D ₁	D ₂	D ₃		D ₁	D ₂	D ₃
1A Std Dev Coeff Var, %	12	73.9	7246.0 175.0 2.4	5.9 0.95 16.1	4.43 0.55 12.4	3.07 0.81 26.4	1.93 0.57 29.3	5127.0 151.0 0.03	3.79 1.01 26.6	1.86 0.26 14.2
1B Std Dev Coeff Var, %	14	90.4	6936.0 245.0 3.5	6.74 0.46 6.8	4.98 0.40 8.0	2.71 0.22 8.0	1.58 0.49 3.1	4988.0 129.0 0.03	4.33 0.80 18.5	1.77 0.22 12.3
2 Std Dev Coeff Var, %	11	85.0	7016.0 36.0 0.5	5.79 0.47 8.0	4.34 0.37 8.5	2.44 0.25 10.3	1.14 0.12 10.6	4988.0 80.0 0.02	3.66 0.36 9.8	1.47 0.52 35.3
3 Std Dev Coeff Var, %	10	96.5	7030.0 33.0 0.4	11.3 1.54 13.6	8.17 1.17 14.3	3.70 0.92 24.9	1.93 0.91 47.3	5012.0 47.0 0.01	6.92 0.87 12.5	2.23 0.41 16.2
4 Std Dev Coeff Var, %	11	97.5	7015.0 29.0 0.4	3.26 0.93 28.7	2.92 0.80 27.5	2.39 0.79 33.2	1.81 0.68 37.4	4035.0 30.0 0.01	2.15 0.57 26.4	1.55 0.46 31.1
5 Std Dev Coeff Var, %	11	95.1	7032.0 23.0 0.3	7.60 0.53 7.0	5.39 0.70 13.1	2.77 0.68 24.6	1.54 0.47 30.3	5018.0 66.0 0.01	4.66 0.37 7.9	1.85 0.27 14.1
6 Std Dev Coeff Var, %	11	80.2	7040.0 32.0 0.5	4.56 0.62 13.5	3.66 0.67 18.3	2.47 0.33 13.4	1.61 0.25 15.6	5011.0 50.0 0.01	2.91 0.45 15.6	1.62 0.23 13.9

(Continued)

Note: 1°F = -17°C; 1 lbf = 4.448 N; 1 mil = 25.4 microns.

Table 1 (Concluded)

Item	No. of Tests	Mean Pavement Temperature, °F	1000-lb Load				5000-lb Load					
			Mean Peak-Peak Force, lb	Mean Deflection, mills				Mean Peak-Peak Force, lb	Mean Deflection, mills			
				D ₁	D ₂	D ₃	D ₄		D ₁	D ₂	D ₃	D ₄
7 Std Dev Coeff Var, %	1	77.3	7090.0	4.40	3.30	2.30	1.50	5130.0	3.00	2.20	1.50	1.00
			--	--	--	--	--	--	--	--	--	--
			--	--	--	--	--	--	--	--	--	--
8 Std Dev Coeff Var, %	19	80.8	7103.0	9.03	6.15	3.11	1.57	5026.0	5.46	3.94	1.75	0.98
			106.0	1.21	0.70	0.84	0.68	73.0	0.90	0.65	0.18	0.30
			1.5	13.4	11.4	27.2	43.6	0.01	16.6	16.5	10.5	30.3
A Std Dev Coeff Var, %	14	87.1	7116.0	10.60	8.94	3.56	1.75	5044.0	6.34	5.12	2.32	1.04
			202.0	2.61	2.71	0.72	0.57	86.0	1.29	1.05	0.44	0.37
			2.8	24.6	24.3	20.3	32.6	0.02	20.4	20.5	16.5	35.5
B Std Dev Coeff Var, %	12	85.0	7087.0	3.53	2.98	2.18	1.50	5159.0	2.47	2.08	1.50	0.95
			56.0	0.35	0.35	0.13	0.13	103.0	0.28	0.24	0.11	0.20
			0.7	9.8	11.7	5.8	8.5	0.02	11.3	11.7	7.5	22.6
C Std Dev Coeff Var, %	9	82.2	7028.0	12.16	8.48	2.79	1.33	5051.0	7.18	5.05	1.50	0.86
			43.0	3.97	2.68	0.44	0.33	108.0	2.07	1.32	0.47	0.12
			0.6	32.6	31.6	15.6	25.1	0.02	28.9	26.1	9.5	13.5
E Std Dev Coeff Var, %	11	82.4	7236.0	9.37	6.74	2.78	1.29	5076.0	5.45	3.99	1.50	0.92
			118.0	0.72	0.59	0.34	0.16	101.0	0.47	0.31	0.11	0.12
			1.6	7.6	8.8	12.2	12.7	0.02	8.6	7.8	9.9	12.1
F Std Dev Coeff Var, %	12	77.5	7019.0	7.66	5.88	2.76	1.36	5053.0	4.9	3.81	1.50	0.92
			45.0	0.72	0.52	0.18	0.25	35.0	0.5	0.35	0.11	0.12
			0.6	9.5	8.8	6.6	18.4	0.01	10.1	9.2	7.5	12.1
G Std Dev Coeff Var, %	12	74.0	7022.0	8.01	6.33	3.10	1.51	5010.0	4.93	3.89	1.96	0.97
			23.0	0.62	0.53	0.30	0.17	49.0	0.38	0.34	0.12	0.11
			0.3	7.8	8.3	9.5	11.5	0.01	7.8	8.7	10.6	11.5

Table 2
Pavement Characteristics for PTF Items

Item	Layer No. 1		Layer No. 2		Layer No. 3		Layer No. 4		Est. at time of test
	Thickness in.	Type	Thickness in.	Type	Thickness in.	Type	Thickness in.	Type	
1A	7.5	Bituminous concrete	20.5	Subbase	--	Subgrade	--	Subgrade	1,797,000
1B	7.5	Bituminous concrete	14.0	Subbase	--	Subgrade	--	Subgrade	2,356,000
2	8.5	Bituminous concrete	8.0	Subbase	--	Subgrade	--	Subgrade	2,356,000
3	2.5	Bituminous concrete	8.0	Aggregate lime pozzolan	8.0	Subbase	--	Subgrade	2,356,000
4	2.5	Bituminous concrete	8.0	Aggregate cement	8.0	Subbase	--	Subgrade	2,356,000
5	2.5	Bituminous concrete	8.0	Aggregate bituminous	8.0	Subbase	--	Subgrade	2,356,000
6	10.5	Bituminous concrete	8.0	Subbase	--	Subgrade	--	Subgrade	2,356,000
7	9.5	Bituminous concrete	8.0	Subbase	--	Subgrade	--	Subgrade	2,356,000
8	8.0	Bituminous concrete	8.0	Subbase	--	Subgrade	--	Subgrade	2,356,000
A	2.5	Bituminous concrete	4.0	Aggregate cement*	8.0	Subbase	--	Subgrade	2,356,000
B	2.5	Bituminous concrete	6.0	Aggregate cement*	8.0	Subbase	--	Subgrade	2,356,000
C	2.5	Bituminous concrete	6.0	Aggregate cement**	8.0	Subbase	--	Subgrade	2,356,000
E	4.0	Bituminous concrete	8.0	Crushed stone	8.0	Subbase	--	Subgrade	2,356,000
F	5.5	Bituminous concrete	6.0	Aggregate lime pozzolan	8.0	Subbase	--	Subgrade	2,356,000
G	5.5	Bituminous concrete	4.0	Aggregate lime pozzolan	8.0	Subbase	--	Subgrade	2,356,000

Note: 1 in. = 2.54 cm.

* Limestone aggregate.

** Slag aggregate.

on these samples in accordance with the procedures outlined in Appendix A. Average results of the subgrade tests are presented in Figure 1. It should be noted that undisturbed samples gave higher modulus values than disturbed samples. The granular subbase results are presented in Figure 2.

RELATIONSHIP OF LAYERED ELASTIC THEORY TO MEASURED DEFLECTIONS

GENERAL

The first assumption in developing this procedure is that dynamic deflections correspond to those deflections predicted from the layered elastic theory. To validate this assumption experimental data were compared with results from two computer programs. The first is the Shell BISAR computer program, based on the layered elastic theory, which relates stress and strain in each layer to a load applied at the surface of a pavement. The other program, entitled CHEVIT,¹⁰ gives a nonlinear approach to the solution of the modulus of the lower layers by using laboratory stress-modulus relationships for granular and subgrade layers. Those layers are divided into sublayers for which the stress is calculated initially, and from the laboratory stress-modulus relationship a new modulus is computed. With this modulus, the program again computes the stress. The program iterates until a solution is obtained for modulus and stress.

LINEAR ANALYSIS

To determine the applicability of the deflection basin to the layered elastic analysis, the BISAR computer program was initially used. The modulus values for the AC surface layers were obtained from the 16-Hz relationship¹¹ presented in Figure 3. An evaluation of data collected with the WES 16-kip vibrator on specially constructed temperature sections at the WES was made using the 16-Hz modulus versus temperature relationships. The test sections were small (approximately 20 by 20 ft) and consisted of varying thickness of AC over a lean clay (CL) subgrade. The design of these sections considered the thickness of AC to be the only variable. Tests were conducted over a wide range of temperatures. Modulus values for the AC as determined from Figure 3 were used in the

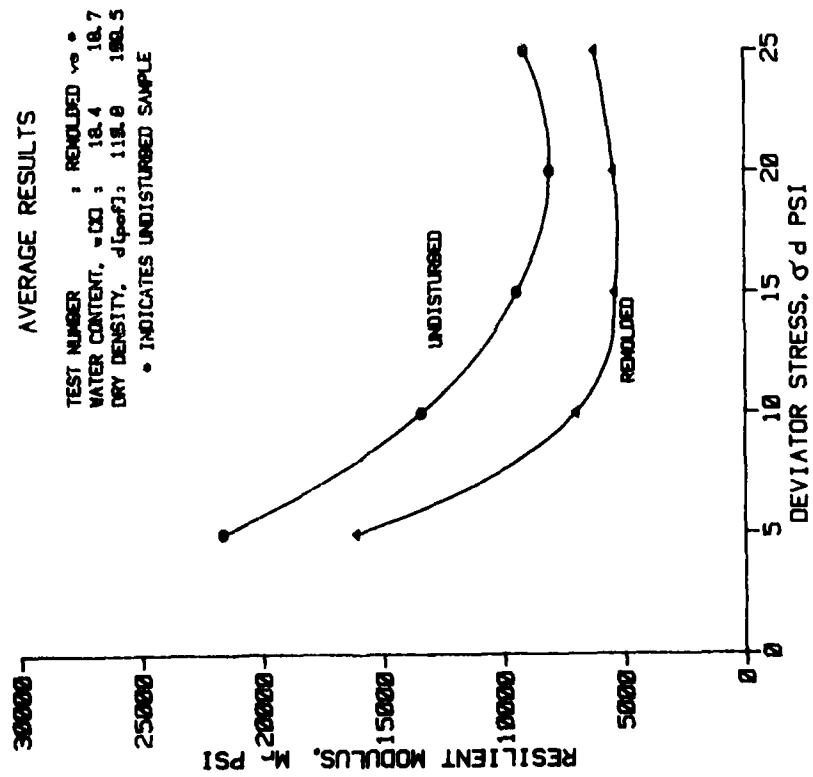


Figure 1. Average results of resilient modulus tests on PTRF subgrade material (1 psi = 703 kg/m²)

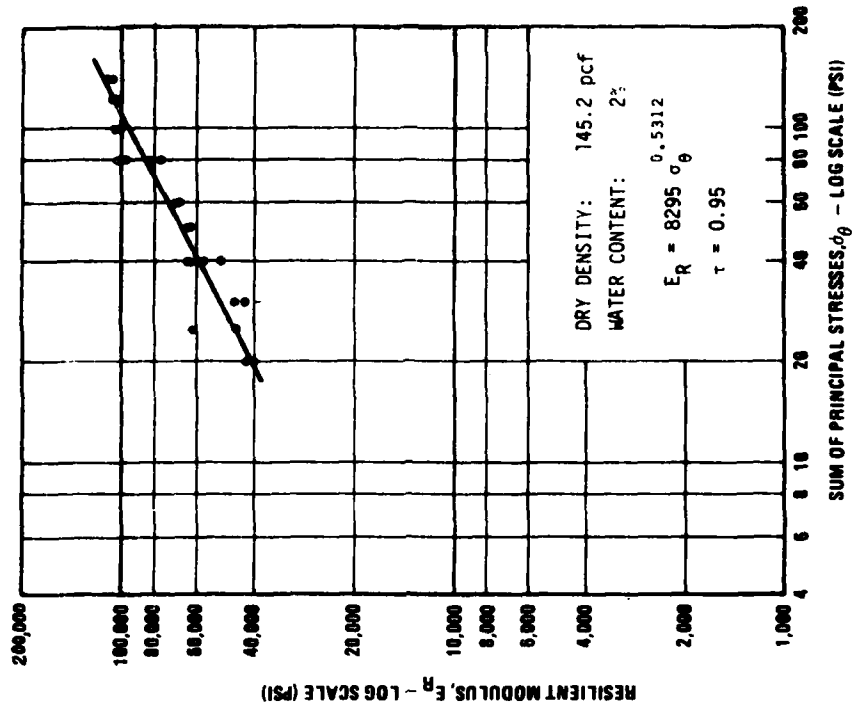


Figure 2. Results of resilient modulus tests on PTRF subbase material (1 psi = 703 kg/m²; 1 pcf = 16.02 kg/m³)

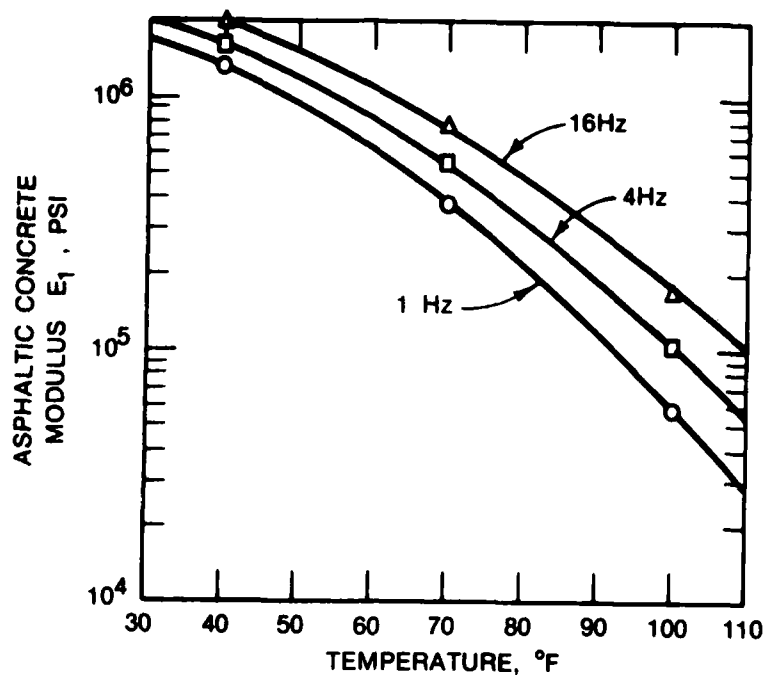


Figure 3. Modulus-temperature relationships for AC surfacing (1 psi = 703 kg/m²; 1°F = -17°C) (after Kingham and Kallas¹¹)

BISAR program to predict deflections. Good correlation was obtained for the temperature test section between the deflection ratios (deflection at a given temperature to deflection at 70°F) obtained from the experimental results and the results from the BISAR. Therefore, the relationships presented in Figure 3 were selected for determination of the AC modulus values.

Modulus values for the pavement layers other than the AC surface layers of the PTRF were estimated from construction data and based on laboratory results that were collected during the initial construction (not the laboratory results presented in this report). Poor agreement was obtained between the BISAR deflections and the measured deflections for the PTRF sections. Therefore, it was concluded that it is extremely difficult to estimate correct modulus values for pavement layers that have been subjected to extensive traffic and environmental effects.

NONLINEAR ANALYSIS

An analysis was then made using the CHEVIT nonlinear program.

The granular subbase layer was characterized by the laboratory relationships shown in Figure 2. The subgrade resilient modulus relationships in Figure 4 represent the averages of the undisturbed sample tests. Figure 5 shows a typical pavement section (PTRF item 1A). The initial estimate for the modulus of the nonlinear layers, as well as the modulus for the linear layer, is given. Pavement sections for all of the PTRF items are shown in Table 2.

The summation of the strains in the bottom layer to infinity by the layered elastic model tends to give larger deflections than the measured values. To compensate for this effect, a rigid layer was placed in this system model at a depth of 20 ft below the surface. Figure 6 shows a comparison of predicted deflections with and without the rigid boundary to the measured deflections. Note that the basins predicted from CHEVIT using the rigid layer agree better with the Model 2008 Road Rater basins than those predicted without the rigid layer.

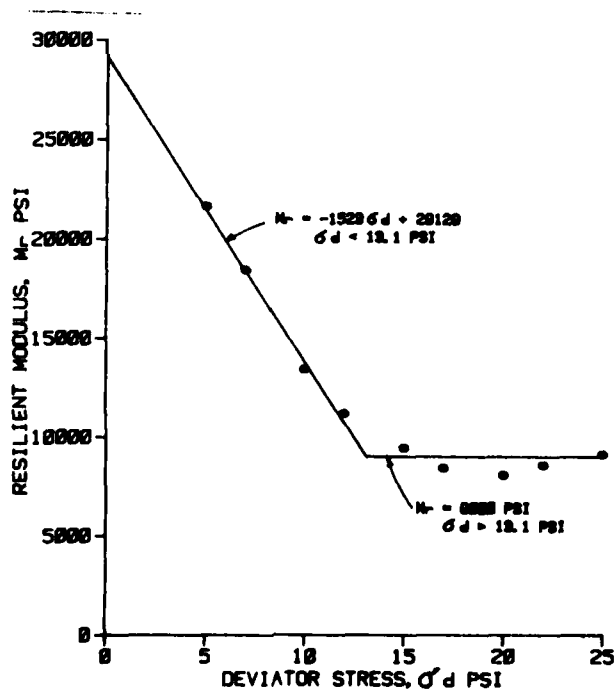


Figure 4. Relationship of subgrade resilient modulus and deviator stress used in CHEVIT
(1 psi = 703 kg/m²)

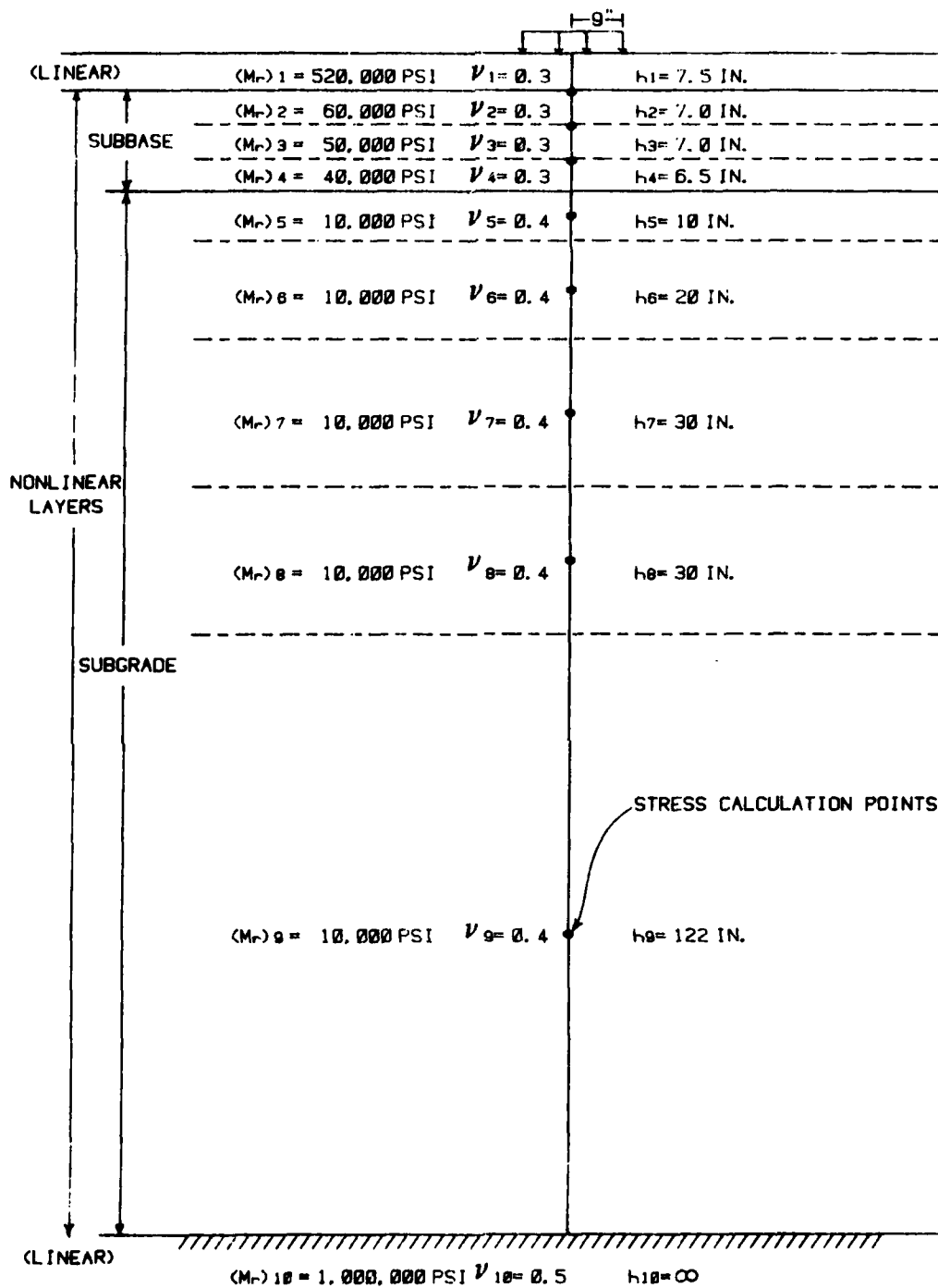


Figure 5. PTRF item 1A pavement section breakdown for CHEVIT input (1 in. = 2.54 cm; 1 psi = 703 kg/m²)

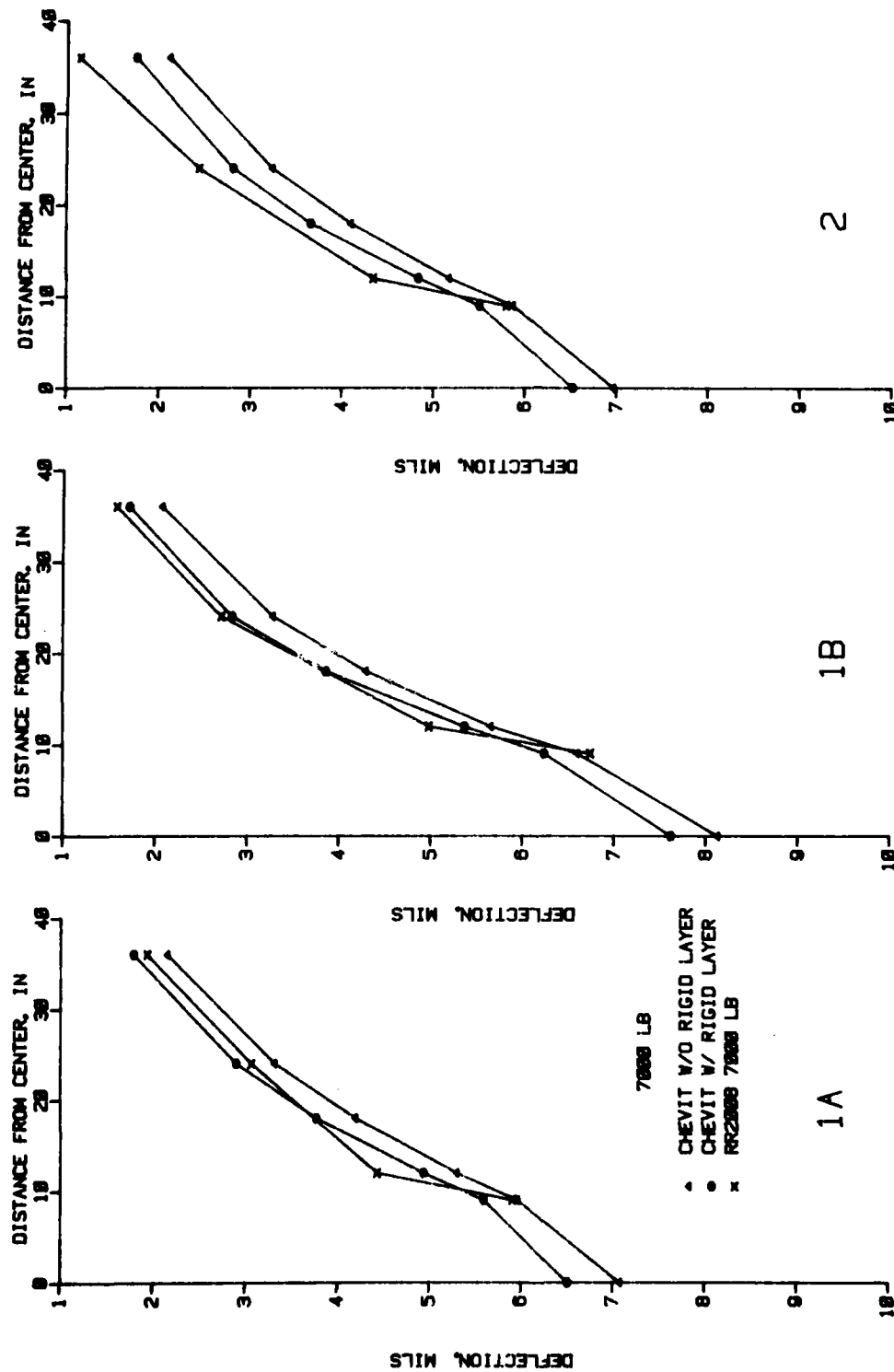


Figure 6. Comparison of layered-elastic deflection basins with and without rigid layer to measured basins (1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

Basins are shown for each of the 15 test items of the PTRF in Figures 7 through 11. Tests with both 5000- and 7000-lb loads were conducted and compared with CHEVIT results. Note the good agreement in the basin data for those sections without the lime and cement-treated base courses. The modulus values for the lime and cement-treated layers were taken from construction records. The heavy traffic on the PTRF at the time of test apparently resulted in cracking of these stabilized layers. Therefore, the stabilized layers had much lower moduli values at the time of the test than those values used in the CHEVIT analysis. This fact explains the variance in measured and predicted deflections in items 3, A, C, E, F, and G shown in Figures 8, 10, and 11. From the results, it appears that the deflection basin is a measurement that can be modeled with a layered elastic theory and, therefore, used to predict the strength parameters of the pavement layers.

EFFECTS OF STATIC PRELOAD

The effects of the static load applied to the pavement surface as a preload with the Model 2008 Road Rater were analyzed using the CHEVIT program. Figure 12 illustrates loading versus time for the Model 2008 Road Rater for the 5000- and 7000-lb tests. The sinusoidal loading applies a minimum and a maximum force to the pavement surface. The magnitudes of these forces range from 500 to 6500 lb for the 5000-lb peak-to-peak force level and from 500 to 7500 lb for the 7000-lb peak-to-peak force. The CHEVIT program was run with forces of 6500 and 1500 lb, and the differences (diff) in predicted deflections from each run were calculated to model the sinusoidal loading of the Road Rater. The results were compared to a run where the force was 5000 lb. Table 3 shows the results of these calculations for PTRF items 1A, 1B, and 2. A maximum difference of 6.3 percent occurred at the 5000-lb force level at 12 in. from the center of the load; however, the percent difference was practically negligible for most comparisons. This analysis indicates that the effect of the static load for computer modeling of the Road Rater results is negligible particularly when the vibrator is operated near the maximum output. Therefore, the static load will be neglected in the determination of the layer modulus values.

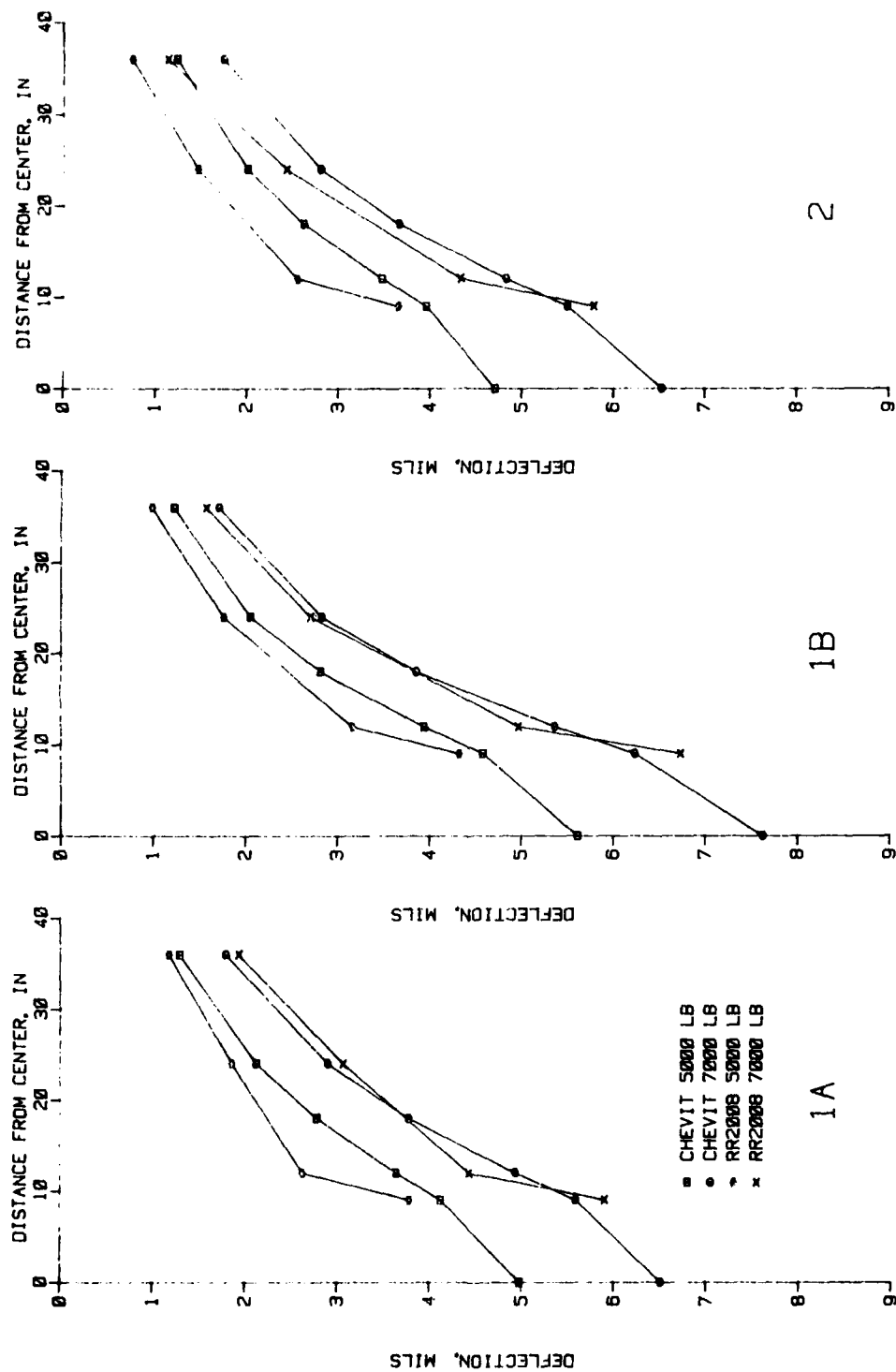


Figure 7. Predicted and measured basins on PTFE items 1A, 1B, and 2 (1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

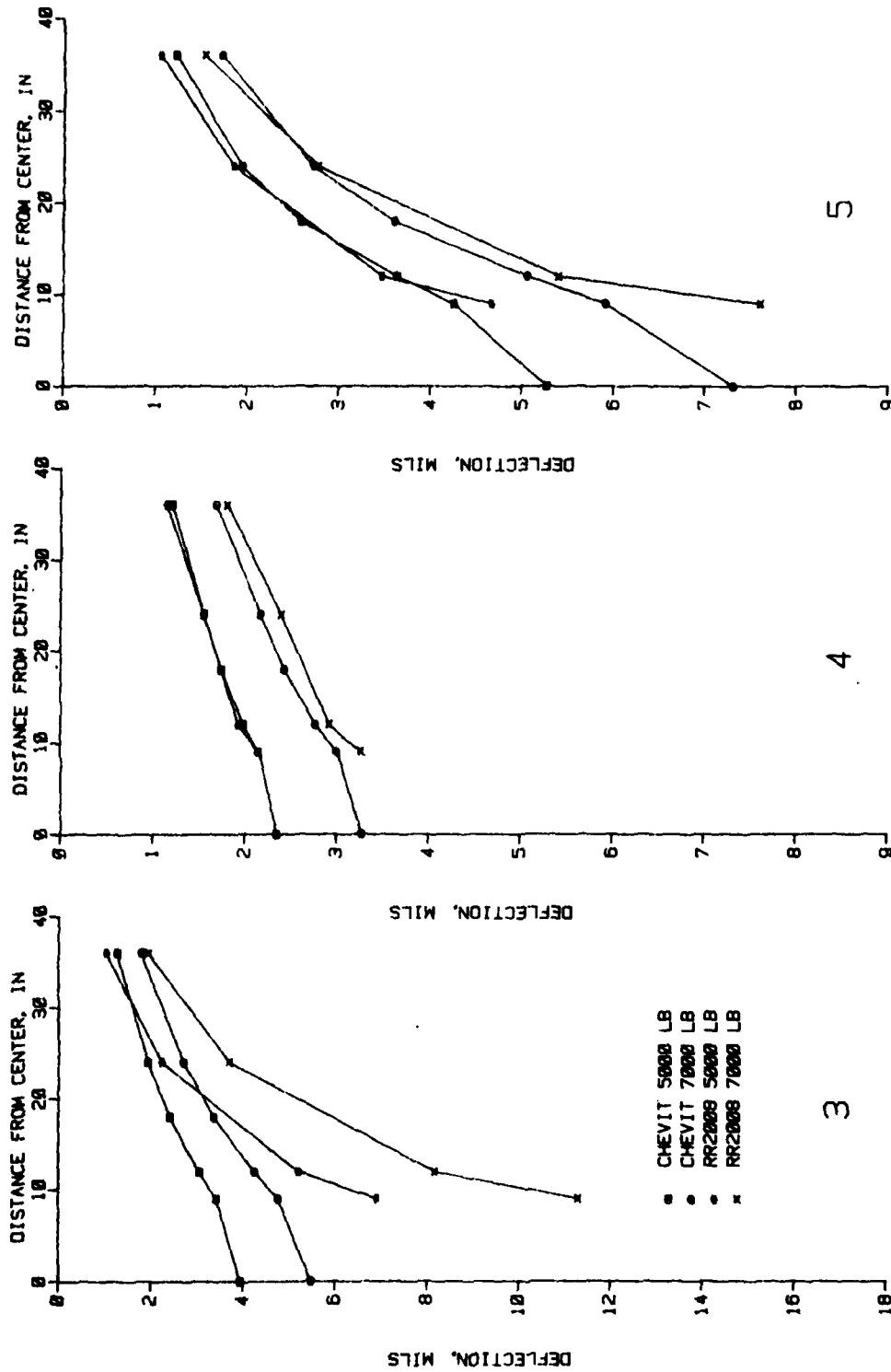


Figure 8. Predicted and measured basins on PTRF items 3, 4, and 5 (1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

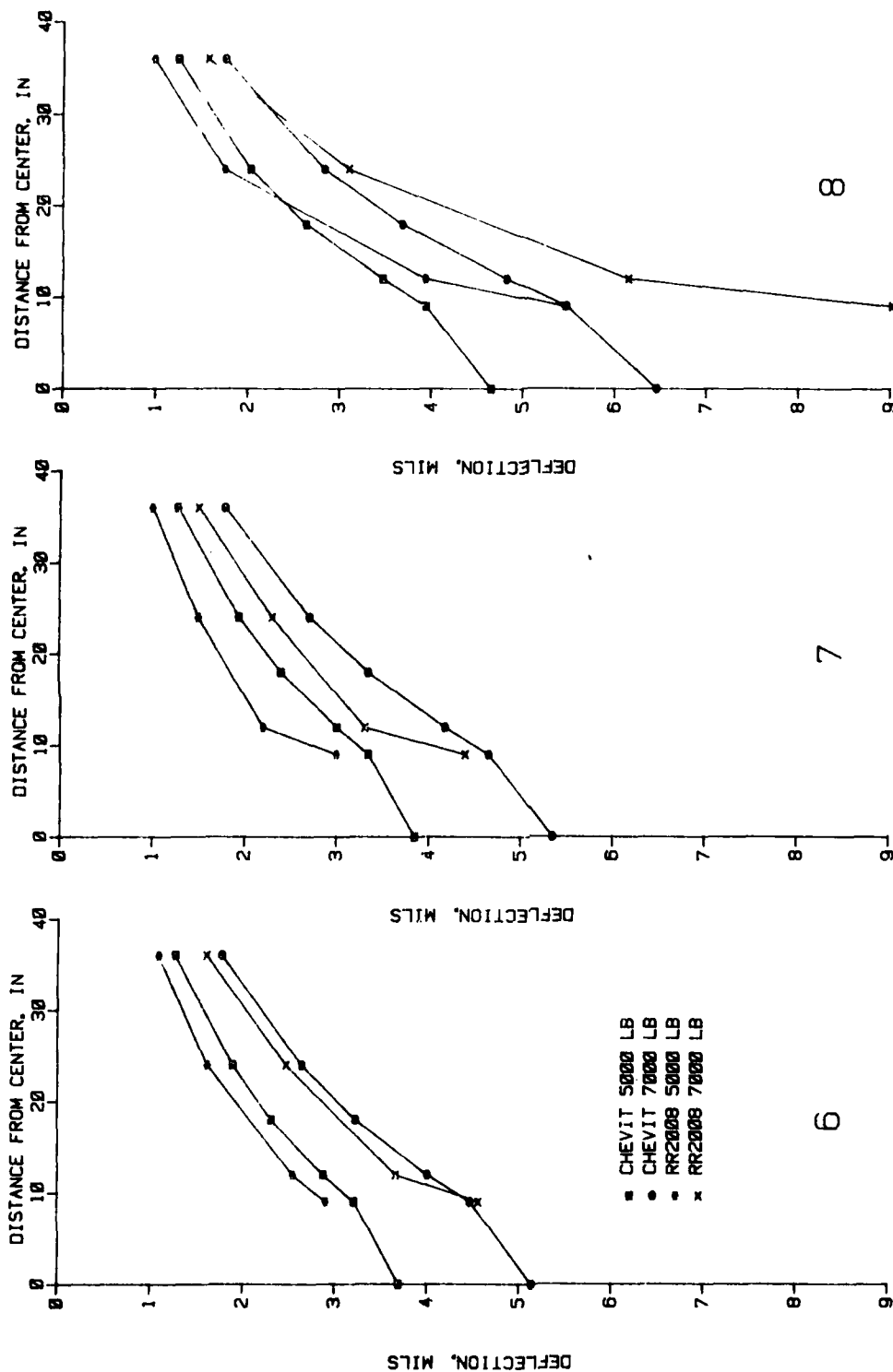


Figure 9. Predicted and measured basins on PTRF items 6, 7, and 8
(1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

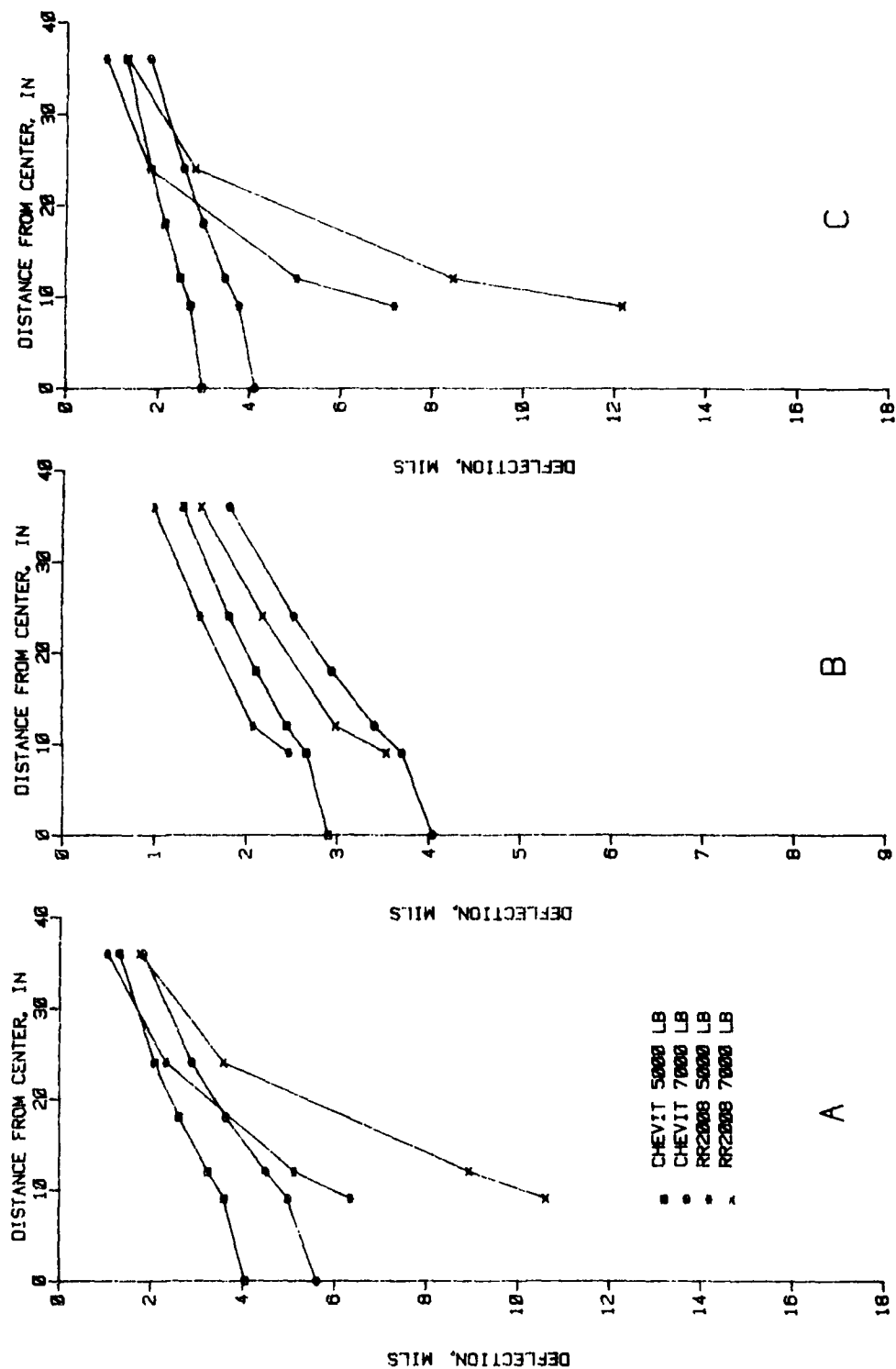


Figure 10. Predicted and measured basins on PTFE items A, B, and C
(1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 44.8 N)

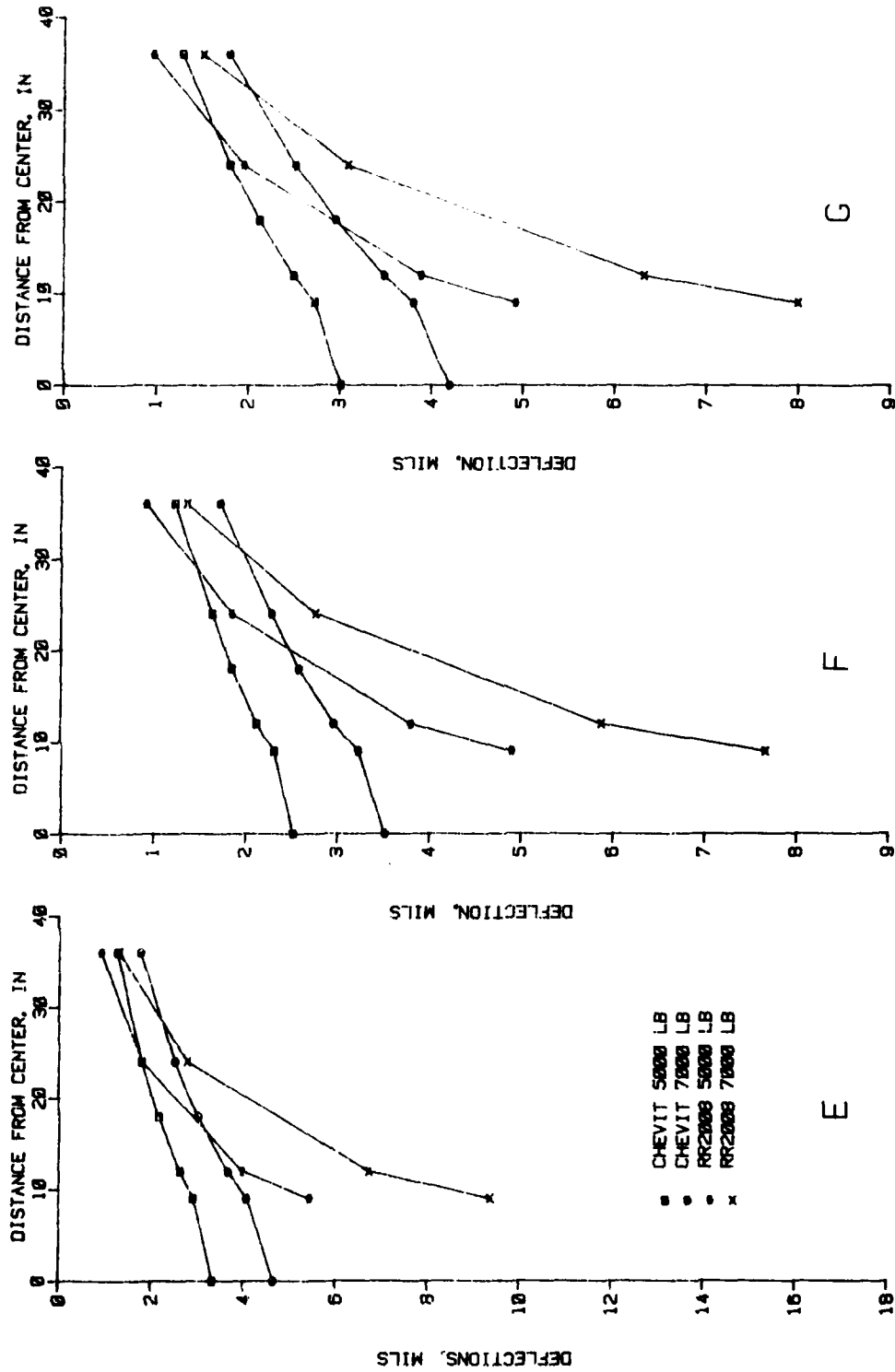


Figure 11. Predicted and measured basins on PTFE items E, F, and G
(1 in. = 2.54 cm; 1 mil = 25.4 microns; 1 lbf = 4.448 N)

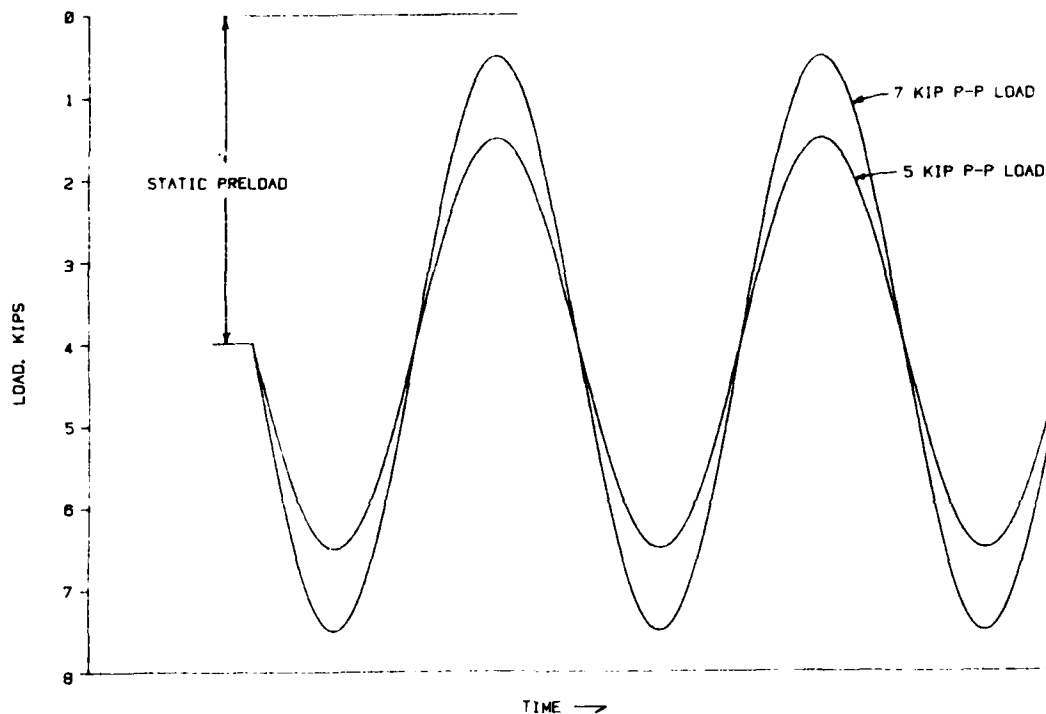


Figure 12. Load versus time history for 5000- and 7000-lb (5- and 7-kip) loads of the Model 2008 Road Rater (1 kip = 4.448 kN)

Table 3
Comparison of the Effects of Static Preload
on PTRF Items 1A, 1B, and 2 Using the CHEVIT Program

Load lb	Deflections, mils, at Cited Distances, in.							
	0	9	12	18	24	36	48	60
<u>PTRF 1A</u>								
6500	6.086	5.232	4.620	3.532	2.712	1.666	1.027	0.715
1500	<u>1.567</u>	<u>1.349</u>	<u>1.194</u>	<u>0.911</u>	<u>0.692</u>	<u>0.408</u>	<u>0.239</u>	<u>0.161</u>
Diff 5000	4.519	3.883	3.426	2.621	2.020	1.258	0.788	0.554
5000	4.797	4.125	3.643	2.782	2.130	1.294	0.790	0.546
Percent Difference	6.2	6.2	6.3	6.1	5.4	2.9	0.3	-1.4
7500	6.925	5.954	5.257	4.022	3.095	1.913	1.187	0.829
500	<u>0.543</u>	<u>0.468</u>	<u>0.415</u>	<u>0.317</u>	<u>0.240</u>	<u>0.140</u>	<u>0.080</u>	<u>0.053</u>
Diff 7000	6.382	5.486	4.842	3.705	2.855	1.773	1.107	0.776
(Continued)								

Note: 1 lbf = 4.448 N; 1 in. = 2.54 cm.

Table 3 (Concluded)

Load lb	Deflections, mils, at Cited Distances, in.							
	0	9	12	18	24	36	48	60
7000	6.507	5.594	4.940	3.778	2.904	1.790	1.107	0.772
Percent Difference	2.0	2.0	2.0	2.0	1.7	1.0	0.0	-0.5
PTRF 1B								
6500	7.128	5.829	5.014	3.598	2.641	1.589	0.970	0.694
<u>1500</u>	<u>1.849</u>	<u>1.511</u>	<u>1.299</u>	<u>0.922</u>	<u>0.660</u>	<u>0.372</u>	<u>0.217</u>	<u>0.153</u>
Diff 5000	5.279	4.318	3.715	2.676	1.981	1.217	0.753	0.541
5000	5.614	4.588	3.944	2.820	2.057	1.221	0.739	0.528
Percent Difference	6.3	6.3	6.2	5.4	3.8	0.3	-1.9	-2.4
7500	8.120	6.644	5.718	4.113	3.030	1.837	1.127	0.806
<u>500</u>	<u>0.646</u>	<u>0.529</u>	<u>0.455</u>	<u>0.323</u>	<u>0.229</u>	<u>0.126</u>	<u>0.072</u>	<u>0.050</u>
Diff 7000	7.474	6.115	5.263	3.790	2.801	1.711	1.055	0.756
7000	7.625	6.237	5.366	3.856	2.835	1.713	1.048	0.750
Percent Difference	2.02	2.0	2.0	1.7	1.2	0.1	0.6	-0.8
PTRF 2								
6500	6.071	5.116	4.492	3.405	2.613	1.618	1.001	0.696
<u>1500</u>	<u>1.471</u>	<u>1.238</u>	<u>1.086</u>	<u>0.817</u>	<u>0.620</u>	<u>0.374</u>	<u>0.226</u>	<u>0.157</u>
Diff 5000	4.600	3.878	3.406	2.588	1.993	1.244	0.775	0.539
5000	4.706	3.963	3.477	2.630	2.013	1.240	0.764	0.532
Percent Difference	2.3	2.2	2.1	1.6	1.0	-0.3	-1.4	-1.3
7500	6.983	5.887	5.171	3.925	3.018	1.874	1.161	0.807
<u>500</u>	<u>0.502</u>	<u>0.423</u>	<u>0.371</u>	<u>0.279</u>	<u>0.211</u>	<u>0.126</u>	<u>0.075</u>	<u>0.052</u>
Diff 7000	6.481	5.464	4.800	3.646	2.807	1.748	1.086	0.755
7000	6.527	5.501	4.831	3.665	2.815	1.746	1.080	0.751
Percent Difference	0.7	0.7	0.6	0.52	0.3	-0.1	-0.6	-0.5

DETERMINATION OF LAYER MODULUS VALUES FROM BASIN DATA

DEVELOPMENT

The deflection basin produced by applying a load to the pavement

with the Model 2008 Road Rater gives four input parameters to the system analysis that can be used to derive the strength parameters of the pavement layers. A program called CHEVDEF was developed to determine a set of modulus values that provide the best fit between a measured deflection basin and a computed deflection basin when given an initial estimate of the modulus values, a range of modulus values, and a set of measured deflections.

Consider the pavement system where:

- a. The modulus is unknown for a number of layers (NL).
- b. The deflection due to plate load is measured at a number of deflection (ND) locations.
- c. ND is greater than NL.

The objective is to determine the set of E's that will minimize the error between the computed deflection Δ and the measured deflection RRD. To accomplish the objective, a relationship was developed for the deflection at a point j as a function of the unknown E's, i.e.,

$$\Delta_j = f(E_1, E_2 \dots E_{NL})$$

then the error at a position where the deflection was measured is

$$RRD_j - \Delta_j = RRD_j - f(E_1, E_2, \dots E_{NL})$$

This expression is then squared and summed with respect to each measured deflection

$$\sum_{j=1}^{ND} \text{ERROR}^2 = \sum_{j=1}^{ND} \left[RRD_j - f_j(E_1 \dots E_{NL}) \right]^2$$

To minimize the error with respect to an unknown E, the partial derivative of the error function is taken with respect to the E. By taking a derivative with respect to each unknown E, then a set of NL equations is obtained that can be solved giving the set of E's for the minimum error between the measured basin and the computed basin.

First, a set of E values is assumed and the deflection Δ_j^0 is computed corresponding to the measured deflection RRD_j . Each unknown

E is varied individually and a new set of deflections is computed for each variation. Using the two computed deflections and the two values of each E, a function is determined for each deflection. For example, let

$$El = \log_{10} E$$

Then the deflection at location l is given as a function of E_l , i.e.,

$$\Delta_l = A_{ll} + S_{ll}El_l$$

where

$$S_{ll} = \frac{\Delta_l^0 - \Delta_l^1}{El_l^0 - El_l^1}$$

$$A_{ll} = \Delta_l^0 - S_{ll}El_l^0$$

$$El_l^0 = \log_{10} \text{ of first assumed value of } E_l$$

$$El_l^1 = \log_{10} \text{ of } E_l \text{ after the variation}$$

$$\Delta_l^0 = \text{computed deflection at position l for } E_l^0$$

$$\Delta_l^1 = \text{computed deflection at position l for } E_l^1$$

Likewise, functions are determined for each deflection and each unknown E, resulting in $j = 1$ to ND and $i = 1$ to NL. Then

$$\Delta_j = A_{ji} + S_{ji}El_i$$

To write an expression for Δ_j as a function of all E's, the following is used

$$\Delta_j = \Delta_j^0 + (\text{changes in } \Delta_j^0 \text{ due to changes in the E's})$$

Consider when the modulus of layer changes from E_l^0 to E_l^1 , the change in Δ_j would be $S_{ji}(El_l^1 - El_l^0)$.

Thus

$$\Delta_j = \Delta_j^0 + \sum_{i=1}^{NL} S_{ji}(El_i - El_i^0)$$

The value of Δ_j^0 can be expressed in terms of any of the unknown E's ,
i.e., E_{NL} , as

$$\Delta_j^0 = A_{jNL} + S_{jNL} E_{NL}^0$$

The expression for Δ_j now becomes

$$\Delta_j = A_{jNL} + S_{jNL} E_{NL}^0 + \sum_{i=1}^{NL} S_{ji} (E_{li} - E_{li}^0)$$

The error squared for the jth position is $(RRD_j - \Delta_j)^2$ or

$$ERROR_j^2 = \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E_{NL}^0 + \sum_{i=1}^{NL} S_{ji} (E_{li} - E_{li}^0) \right] \right\}^2$$

The summation of the error for all readings is

$$\sum_{j=1}^{ND} ERROR_j^2 = \sum_{j=1}^{ND} \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E_{NL}^0 + \sum_{i=1}^{NL} S_{ji} (E_{li} - E_{li}^0) \right] \right\}^2$$

If a weight term W_j for each reading is to be applied, then the expression becomes

$$\sum_{j=1}^{ND} [W_j - (ERROR)]^2 = \sum_{j=1}^{ND} \left\{ W_j \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E_{NL}^0 + \sum_{i=1}^{NL} S_{ji} (E_{li} - E_{li}^0) \right] \right\} \right\}^2$$

Taking the partial with respect to each E and setting the partial equal to zero, the following is obtained:

$$0 = \sum_{j=1}^{ND} S_{jk} W_j \left\{ RRD_j - \left[A_{jNL} + S_{jNL} E_{NL}^0 + \sum_{i=1}^{NL} S_{ji} (E_{li} - E_{li}^0) \right] \right\}$$

If the equations derived are put in the form

$$[B] \{E\} = \{C\}$$

the $\{C\}$ terms are the constant part of the equation. For $k = 1$ to NL

$$C_k = \sum_{j=1}^{ND} S_{jk} W_j \left[RRD_j - \left(A_{jNL} + S_{jNL} E_{NL}^0 - \sum_{i=1}^{NL} S_{ji} E_{li}^0 \right) \right]$$

and the $[B]$ for $k = 1$ to NL and $i = 1$ to NL is

$$B_{ki} = \sum_{j=1}^{ND} S_{jk} W_j S_{ji}$$

If the weight term is chosen to be $W_j = \frac{1}{RRD_j}$, the result is the same as developing the equation from

$$ERROR_j = \frac{RRD_j - \Delta_j}{RRD_j}$$

which is a percent type error. The solution of the equation is the set of E's that minimizes the percent error. The efficiency of the procedure will depend on how well the functions represent the actual relationship between the computed deflection and the E's.

It appears that as long as the final E values are within the initial input limits, the $\Delta = f(\log_{10} E)$ is a good representation of the relationship.

A computer program named CHEVDEF, consisting of the procedure described above, was used in developing the pavement evaluation procedure reported herein. CHEVDEF uses the CHEVRON layered elastic program as a subroutine to compute surface deflections. A flowchart, input format, example input, example output, and a listing of CHEVDEF are presented in Appendix B.

The limitations of this approach are that the layered elastic theory assumes a uniform pressure applied to the surface of the pavement. With the Model 2008 Road Rater, the load is applied through a rigid circular plate with the center deflection measured on top of that plate. Therefore, a difference does exist in the measured center deflection and a deflection computed from layer elastic procedures at the center of the load area, as illustrated by Fossberg¹² in Figure 13. Note that the elastic layer solution and field data coincide at approximately three-fourths of the radius of the plate. In order to determine the optimum spacing for the deflection measurements, computations such as shown in Figures 14 and 15 were made with the CHEVDEF program for flexible and rigid pavements, respectively. Spacing distances of 0, 4.5, 6, and 9 inches were used for the computations. Varying these distances caused little change in the subgrade modulus for either the flexible or the rigid pavement. There was variation in the surface modulus on the flexible pavement. Based on the temperature-frequency relationship presented in Figure 3, the modulus of the asphalt layer should be 520,000 psi. Thus, from Figure 15, a distance between 4.5 and 6 in. appears to produce the best results.

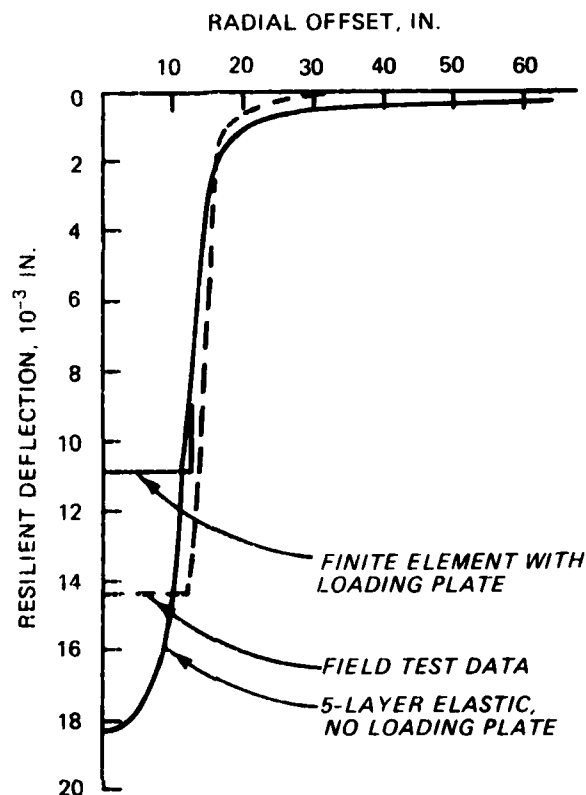


Figure 13. Patterns of resilient deflections under a 24-in.-diameter plate (plate pressure = 4 psi) directly on the subgrade (1 in. = 2.54 cm) (after Fossberg¹²)

SENSITIVITY ANALYSIS

To evaluate the accuracy of the CHEVDEF, an analysis was made on a thin and a thick pavement section. The CHEVRON program was used to calculate deflections for the two pavement sections. These deflections were used as measured deflections for this analysis so that an error associated with field measurements would be eliminated. Tables 4 and 5 present the results. The modulus values listed as correct values in these tables were input to the CHEVRON program to give the deflections that were used as measured deflections in CHEVDEF. In the first case, the initial estimate for modulus was higher than the correct values. The initial estimate was lower than the correct values for the second

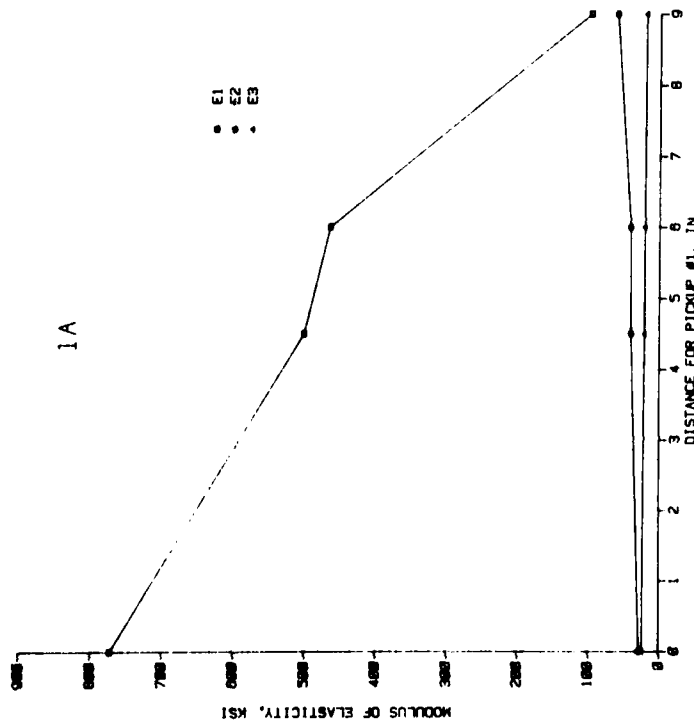


Figure 14. Effect of distance from center of rigid plate on predicted modulus for flexible pavement (1 ksi = 6.89 MPa; 1 in. = 2.54 cm)

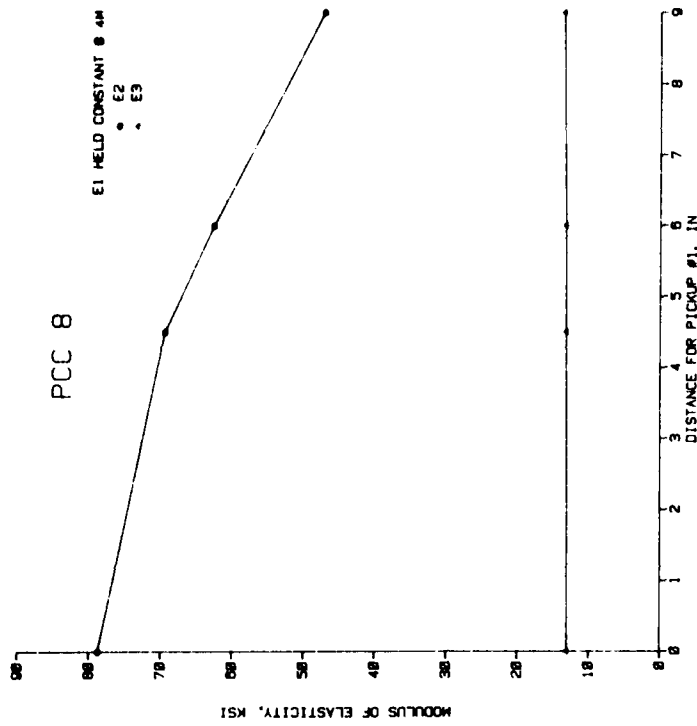


Figure 15. Effect of distance from center of rigid plate on predicted modulus for rigid pavement (1 ksi = 6.89 MPa; 1 in. = 2.54 cm)

Table 4

Reproducibility of the CHEVDEF Program for a Thin Section

	Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflections, mils, at Cited Distance from ϕ of Load, in.			
	E_1	E_2	E_3	E_4	Δ_1	Δ_2	Δ_3	Δ_4
	1.5	4.0	8	226.5	4.5	12	24	36
First case:								
Correct	200,000	350,000	45,000	15,000	10.68	7.818	4.714	2.981
Assumed	450,000	800,000	100,000	30,000	5.1117	3.8035	2.3464	1.5035
Range (min-max)	(100,000- 600,000)	(200,000- 900,000)	(20,000- 150,000)	(5,000- 70,000)				
Final	156,192	371,545	47,638	14,900	10.6439	7.7864	4.7103	2.9842
Second case:								
Correct	200,000	350,000	45,000	15,000	10.68	7.818	4.714	2.981
Assumed	60,000	100,000	15,000	10,000	21.9558	14.2438	7.2535	4.2921
Range (min-max)	(50,000- 300,000)	(50,000- 500,000)	(10,000- 80,000)	(5,000- 30,000)				
Final	50,000	444,279	54,032	14,845	10.9201	7.7747	4.7400	3.0141
Third case:								
Correct	200,000	350,000	45,000	15,000	10.68	7.818	4.714	2.981
Assumed	100,000	600,000	35,000	25,000	8.2731	5.6602	2.9723	1.7357
Range (min-max)	(50,000- 300,000)	(200,000- 700,000)	(20,000- 80,000)	(5,000- 30,000)				
Final	90,830	509,630	48,784	15,114	10.5267	7.7027	4.6783	2.9597

Note: 1 psi = 703 kg/m²; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

Table 5
Reproducibility of the CHEVDEF Program for a Thick Section

	Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflections, mils, at Cited Distance from ν of Load, in.			
	E_1 2.5	E_2 8	E_3 8	E_4 221.5	Δ_1 4.5	Δ_2 12	Δ_3 24	Δ_4 36
First case:								
Correct	200,000	350,000	45,000	15,000	7.28	5.734	4.1820	2.970
Assumed	450,000	800,000	100,000	30,000	5.5603	4.3504	3.1429	2.2268
Range (min-max)	(100,000- 600,000)	(200,000- 900,000)	(20,000- 150,000)	(5,000- 70,000)				
Final	198,498	352,192	44,808	15,006	7.2798	5.734	4.1821	2.970
Second case:								
Correct	200,000	350,000	45,000	15,000	7.28	5.734	4.1820	2.970
Assumed	60,000	100,000	15,000	10,000	15.5701	11.0651	7.0534	4.5442
Range (min-max)	(50,000- 300,000)	(50,000- 500,000)	(10,000- 80,000)	(5,000- 30,000)				
Final	196,507	345,207	47,571	14,950	7.2656	5.7153	4.1752	2.9727
Third case:								
Correct	200,000	350,000	45,000	15,000	7.28	5.734	4.1820	2.970
Assumed	100,000	600,000	35,000	25,000	5.4674	4.0482	2.8051	1.8720
Range (min-max)	(50,000- 300,000)	(200,000- 700,000)	(20,000- 80,000)	(5,000- 30,000)				
Final	173,674	380,337	47,545	15,078	7.1869	5.6577	4.1483	2.9536

Note: 1 psi = 703 kg/m²; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

case. In the third case, the initial estimate was alternated between low and high values. The program reasonably reproduced all modulus values for the thick section but varied from the correct values for the thin upper layers for the thin section. The values for the the two bottom layers were very close even for the thin section.

To determine the reproducibility for different spacings of deflections, the data for the thick section were selected. Table 6 lists the results of this analysis. No significant difference occurred due to the location of the deflection with respect to the final value of modulus for up to four layers.

Another check was made on a typical section with a stiff (stabilized) layer. Table 7 summarizes the results. Again the program produced a good approximation of the correct values for the four-layer system.

To determine the sensitivity of the CHEVDEF program to the Poisson's ratio of each layer, an analysis was made using the thick section. The Poisson's ratio was varied between 0.2 and 0.5 for each layer. Figure 16 shows the change in modulus values for these variations in the Poisson's ratio. There is little effect on the predicted modulus values when the Poisson's ratios for layer 2 and layer 3 are varied. The variations are large in layer 1 and layer 2 when the Poisson's ratios of layer 1 and layer 4 are varied. In all cases, there is little variation in the modulus of the lower layers.

A Poisson's ratio of 0.35 will be assigned to all layers above the subgrade, and a ratio of 0.4 will be assigned to the subgrade.

PREDICTION OF LAYER MODULUS VALUES

The CHEVDEF program was used to predict modulus values for the 15 PTKF test items. Table 8 presents the results. Layer 1 includes all the AC material, and the modulus value for this layer was taken from the 16-Hz relationship in Figure 3. The pavement temperature was computed from the surface temperature plus the previous five-day mean.¹³

Basins predicted from the program were not plotted against the measured basins, but the small differences can be seen in the column entitled "Absolute Sum of Differences in Deflections." In each case, this is the sum of the differences in four deflections.

Table 6

Reproducibility of CHEVDEF Program for a Thick Section
with Variable Deflection Distances

		Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflection, mils			
		E_1	E_2	E_3	E_4	Δ_1	Δ_2	Δ_3	Δ_4
		1.5	4	8	226.5	Distance, in.			
First case:						0	9	18	30
Correct		200,000	350,000	45,000	15,000	7.488	6.504	4.892	3.535
Assumed		300,000	400,000	60,000	20,000				
Range (min-max)		(100,000- 400,000)	(200,000- 500,000)	(30,000- 70,000)	(10,000- 30,000)				
Final		175,264	367,258	45,721	15,021	7.4880	6.5039	4.8918	3.5349
Second case:						4.5	12	24	36
Correct		200,000	350,000	45,000	15,000	7.280	5.734	4.182	2.970
Assumed		300,000	400,000	60,000	20,000				
Range (min-max)		(100,000- 400,000)	(200,000- 500,000)	(30,000- 70,000)	(10,000- 30,000)				
Final		198,498	352,192	44,808	15,006	7.2798	5.7340	4.1821	2.9700
Third case:						9	18	30	42
Correct		200,000	350,000	45,000	15,000	6.504	4.892	3.535	2.497
Assumed		300,000	400,000	60,000	20,000				
Range (min-max)		(100,000- 400,000)	(200,000- 500,000)	(30,000- 70,000)	(10,000- 30,000)				
Final		197,002	357,639	45,586	15,007	6.5033	4.8913	3.5347	2.4969

Note: 1 psi = 703 kg/m^2 ; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

Table 7
Reproducibility of the CHEVDEF Program
for a Section with a Stiff Layer

	Predicted Modulus Values, psi, for Cited Layer Thickness, in.				Computed Deflections, mils, at Cited Distance, in.			
	E_1	E_2	E_3	E_4	Δ_1	Δ_2	Δ_3	Δ_4
	5.0	8.0	8.0	219.0	4.5	12	24	36
Correct	300,000	1,000,000	45,000	10,000	6.371	5.437	4.698	3.821
Assumed	200,000	1,500,000	60,000	15,000	4.9629	4.0108	3.3981	2.6983
Range (min-max)	(100,000- 400,000)	(500,000- 2,000,000)	(30,000- 700,000)	(5,000- 20,000)				
Final	284,249	1,148,323	33,730	10,207	6.3562	5.4204	4.6799	3.8040

Note: 1 psi = 703 kg/m²; 1 in. = 2.54 cm; 1 mil = 25.4 microns.

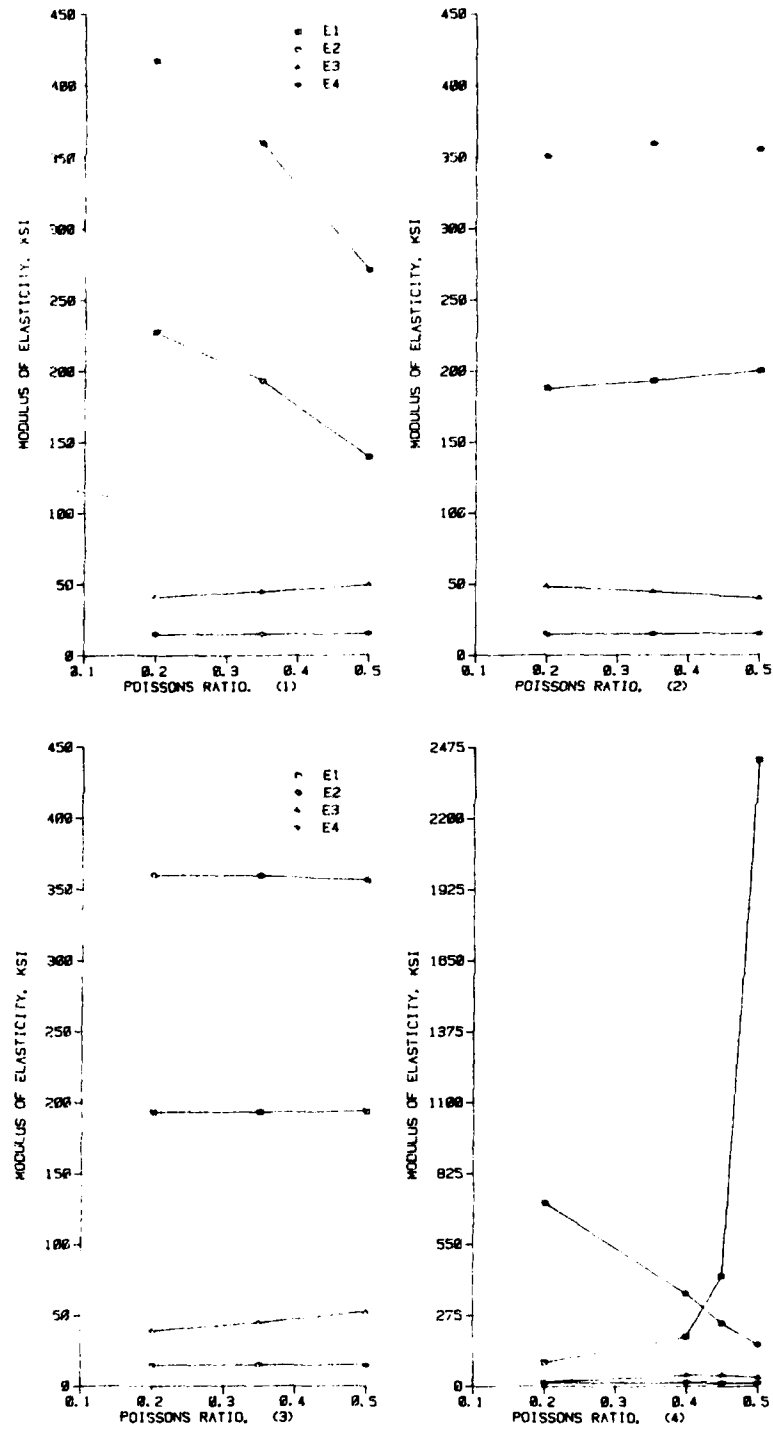


Figure 16. Effect of varying Poisson's ratios (v_1 , v_2 , v_3 , and v_4) on predicted modulus values (1 ksi = 6.89 MPa)

Table 8

 $\therefore \text{bf} = \dots\dots\dots \text{N} ; \text{rsf} = 703 \text{ kg/m}^2$

The stress produced in the subgrade by the Model 2008 Road Rater may not be the stress associated with the design aircraft load. To account for this, two loads were analyzed (5000 and 7000 lb). The modulus values and stresses (vertical, longitudinal, and radial) at the top of the subgrade were calculated for each load level. With these values, a relationship between the modulus and the deviator stress can be developed for stress-dependent subgrades. Table 8 also shows the slope of the line and the intercept, as well as the bulk stress at the top of the subbase layer. There appears to be no relationship to the laboratory results for these values. The values of E for the granular layer are values that satisfy the model deflection basin. The granular material without a binder has very few load transfer properties through bending. Therefore, the model predicted lower modulus values. Associated with the low modulus value is a high vertical strain in that layer, which is considered a problem in using the layered elastic theory to model granular materials.

DETERMINATION OF SUBGRADE MODULUS FOR EVALUATION

Results from the CHEVDEF program give the relationship for the deviator stress and the modulus for the subgrade materials in the form

$$E = S\sigma_D + I$$

where

E = subgrade modulus

S = slope

σ_D = deviator stress

I = intercept

It is known from Hooke's Law and by definition for resilient modulus that

$$E = \frac{\sigma_D}{\epsilon}$$

where ϵ represents the strain. By substituting and rearranging

$$E = SE\epsilon + I$$

or

$$E = \frac{I}{1 - S\epsilon}$$

If a limiting vertical compressive strain is selected, the modulus of the subgrade can be calculated. For comparisons used in this study, a value of 0.0006 in./in. was selected. This value was taken from an average line drawn on Figure 17 and represents 500,000 repetitions or 25,000 arrival/departures per year for 20 years. The equation for the average line is given as

$$\epsilon_v = AN^B$$

where

ϵ_v = limiting vertical compressive strain in subgrade, in./in.

A = 0.0063548

N = number of strain repetitions

B = -0.17985

The modulus values in Table 9 associated with that strain level will be used for the evaluation of these pavements.

COMPARISON OF SUBGRADE MODULUS VALUES

The design modulus can also be computed from laboratory resilient modulus test results as outlined in Appendix A. The best-fit line for deviator stresses between 5 and 12 psi was calculated and then presented in Table 9. A comparison of the mean subgrade modulus values from the CHEVDEF program analysis (14,201 psi) to the laboratory results (12,864 psi) seems very reasonable.

Another comparison was made to the subgrade strength parameters derived from the DSM method reported by Green and Hall.² The PTRF facility was tested with the WES 16-kip vibrator at the same time that testing was conducted with the Model 2008 Road Rater. Table 10 summarizes results of the DSM evaluation. The subgrade strength factor is the equivalent of the design CBR for the subgrade. The factor is calculated as the CBR required to support a single-wheel load with a 254-sq-in. contact area for 1200 annual departures. The load on the wheel is determined by a correlation with the measured DSM. The relationship of 1500 times CBR was used to compare the design modulus values for the DSM method and for the layered elastic procedure (Figure 18). Except for two items (PTRF items 4 and B) that had very low deflections and high DSM's due to stabilized layers, subgrade strength design parameters approximate each other.

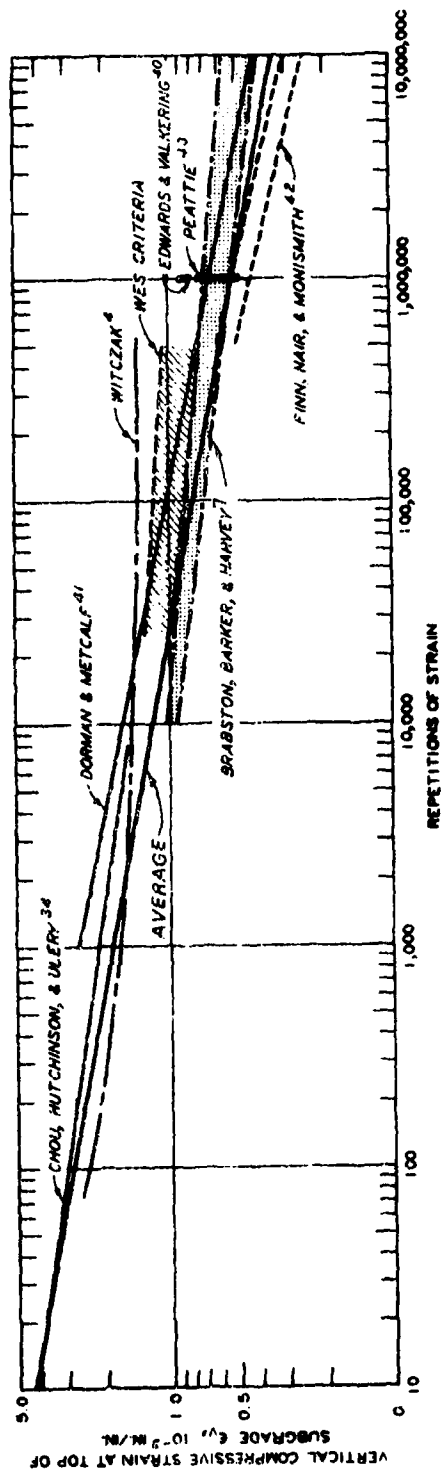


Figure 17. Comparison of subgrade strain criteria (1 in. = 2.54 cm)
(after Barker and Brabston¹⁴)

Table 9
Deviator Stress - Resilient Modulus
Relationships from Laboratory Tests

Sample No.	Type Sample	Slope S	Intercept I	Design E* psi
I-1	Remolded	-1279	18,428	10,424
I-2	Remolded	-1052	15,632	9,585
II-1	Undisturbed	-1181	20,811	12,182
II-2	Undisturbed	- 932	22,581	14,484
III-1	Remolded	-3342	45,998	15,305
III-2	Remolded	-1049	15,089	9,261
III-3	Undisturbed	-1773	38,808	18,804

Mean = 12,864

Standard Deviation = 3,512

Note: 1 psi = 703 kg/m².

* Based on strain level of 0.0006 in./in.

Table 10
DSM Evaluation of the PTRF

PTRF Item*	Temperature Corrected DSM kips/in.	Subgrade Strength Factor	Allowable Gross Aircraft Load, kips	
			254 sq-in. Single Wheel**	127 sq-in. Single Wheel†
1A	1210	6.95	11.3	86.8
1B	1008	9.29	92.7	79.9
2	1331	18.97	122.4	103.8
3	813	11.79	74.7	58.3
4	2286	26.4	210.3	181.9
5	863	9.58	79.4	61.6
6	1542	15.9	141.9	116.8
7	1254	15.2	115.4	96.9
8	657	9.05	60.4	45.5
A	605	11.1	55.7	40.2
B	1634	25.6	150.3	131.9
C	661	8.85	60.8	45.5
E	708	6.49	65.1	48.2
F	859	9.5	79.0	61.3
G	689	9.15	63.3	47.5

Note: 1 kip = 4.448 kN; 1 kip/in. = 1.75 kN/cm; 1 sq in. = 6.45 sq cm.

* See Table 2 for a description of these pavements.

** 1,200 annual departures, 20-year life.

† 25,000 annual departures, 20-year life.

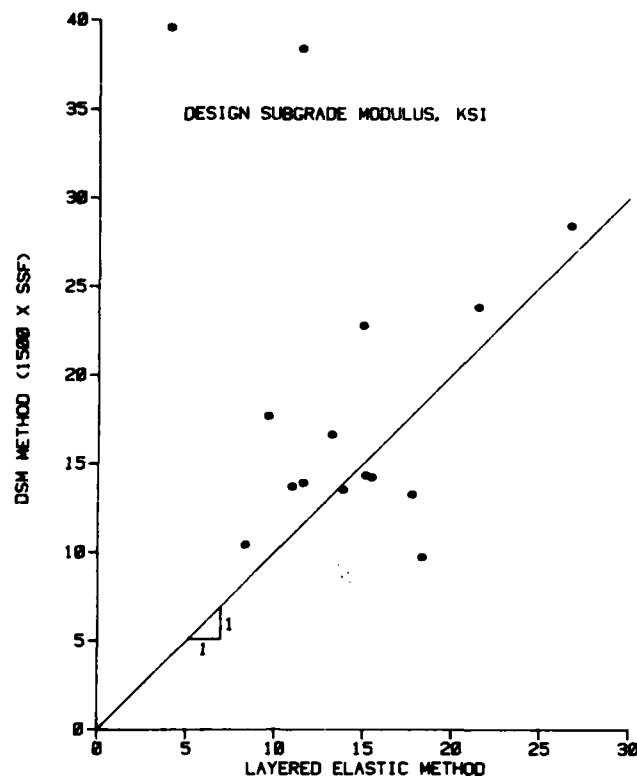


Figure 18. Comparison of subgrade modulus by the DSM and layer elastic method (1 ksi = 6.89 MPa)

EVALUATION OF ALLOWABLE AIRCRAFT LOADS

For the evaluation of the allowable aircraft loads, the PAVEVAL computer program reported by Weiss³ was used. For flexible pavements, this program calculates the vertical compressive strain at the top of the subgrade and the tensile strain at the bottom of the AC layer. These strains are compared to the limiting strain criteria reported by Barker and Brabston.¹⁴ For rigid pavements, the limiting tensile stress in terms of the number of load (stress) repetitions from Parker et al.¹⁵ is considered as

$$\sigma_{RL} = \frac{R}{A + B \log (\text{cov})}$$

where

- σ_{RL} = limiting value of tensile stress, psi
- R = flexural strength, psi
- A = 0.58901

$$B = 0.35486$$

cov = number of coverages (The number of coverages is determined by dividing the number of aircraft departures by the departure-to-coverage ratio. The ratio used for single-wheel gears was 7.94 and for dual-wheel gears was 5.2.)

Example inputs and outputs for evaluation of light aircraft allowable loads on rigid and flexible pavements are given in Appendix C. A comparison of the allowable gross loads for the PTRF items was made between the DSM method and the layered elastic procedure (Figure 19). For comparison purposes, the design loads were calculated for a single-wheel aircraft with 127-sq-in. contact area and 25,000 annual departures.

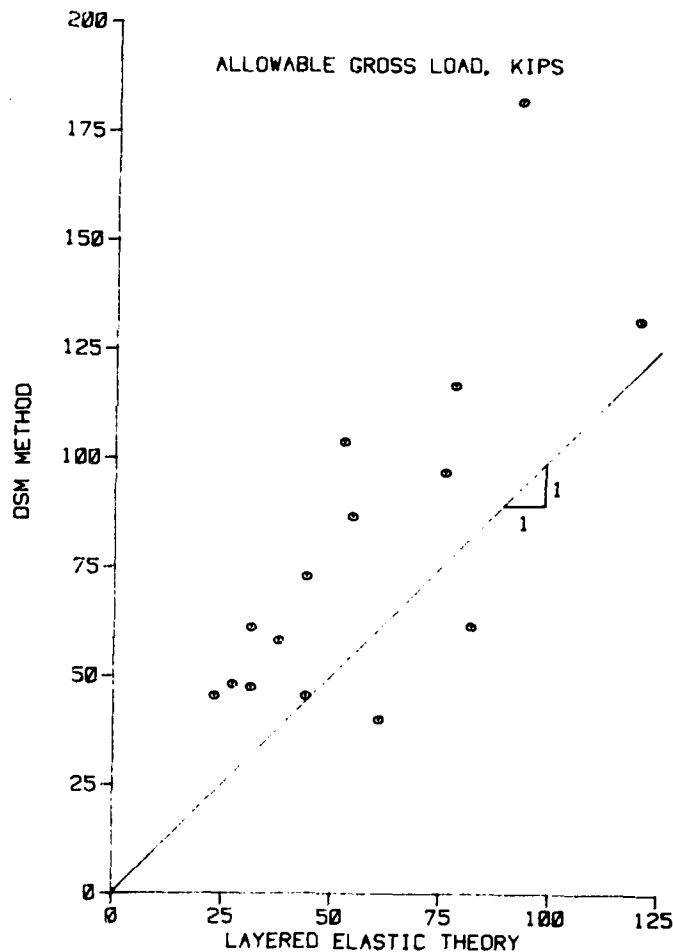


Figure 19. Comparison of allowable gross aircraft loads from the DSM and layered elastic methods (1 kip = 4.448 kN)

For the layered elastic evaluation, the modulus of the AC was selected as 770,000 psi, which corresponds to the 70°F temperature in Figure 3. The modulus of the subbase and base course layers (E2 in three-layer items, and E2 and E3 in four-layer items) were taken from the 7000-lb load in Table 8.

The allowable loads calculated from the DSM method are generally higher than those calculated using PAVEVAL. The controlling strain is shown in Table 11 for each of the PTRF items. The lower allowable loads for the layered elastic evaluations are probably due to the tensile strain controlling and being based on the initiation of a crack in the bottom of the AC rather than the crack propagating through the AC to the surface as was the case in the DSM evaluation (CBR Design System).

Table 11
Allowable Gross Aircraft Loads
from PAVEVAL

PTRF Item	Allowable Gross Aircraft Load kips	<u>Controlling Strain</u>	
		<u>Vertical</u> <u>Subgrade</u>	<u>Tensile</u> <u>AC</u>
1A	54.7		X
1B	44.2		X
2	52.6		X
3	37.9		X
4	92.6	X	
5	82.1	X	
6	77.9		X
7	75.8		X
8	44.2		X
A	61.1	X	
B	120.0	X	
C	23.2		X
E	27.4		X
F	31.6		X
G	31.6		X

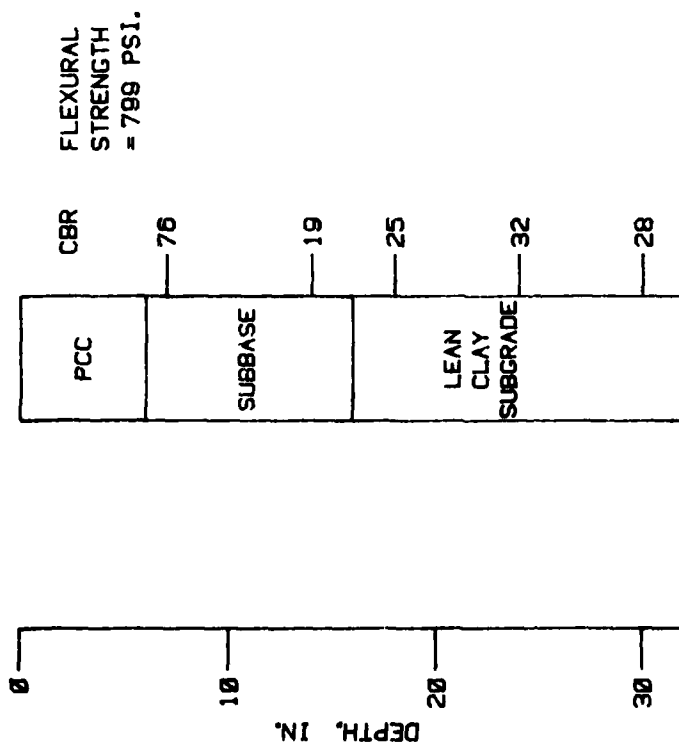
Note: 1 kip = 4.448 kN.

A limited amount of testing was conducted on rigid pavements to verify the applicability of this procedure. Tests with the Model 2008 Road Rater were conducted on a portland cement concrete (PCC) road with

the pavement structure as shown in Figure 20. Laboratory resilient modulus tests were not conducted on the subbase but were conducted on the subgrade material (Figure 21).

Table 12 presents the CHEVDEF program results for this rigid pavement. The subgrade modulus selected for evaluation for rigid pavements is the modulus that is associated with a 5-psi deviator stress¹⁵ and is calculated directly from the slope and intercept derived from the deviator stress-modulus relationship for the 5000- and 7000-lb loads.

Also shown in Table 12 is the modulus for 5-psi deviator stress from the laboratory resilient modulus test. CBR tests were taken to depths of 30 in. The sample taken from the 30- to 45-in. depth indicated a higher strength material (Figure 20). Therefore, the predicted subgrade modulus seems to be a reasonable estimate of the subgrade strength.



NOTE: SAMPLE FOR RESILIENT MODULUS TESTING WAS TAKEN FROM DEPTH 30 TO 45 INCHES.

Figure 20. Pavement structure and test results on PCC pavement (1 in. = 2.54 cm; 1 psi = 703 kg/m²)

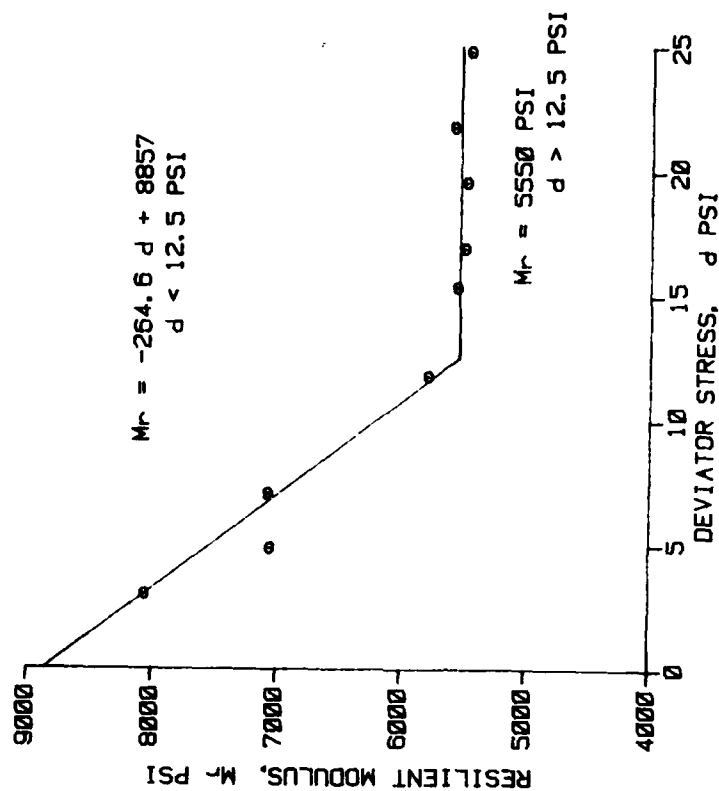


Figure 21. Results of resilient modulus tests on the PCC pavement subgrade material (1 psi = 703 kg/m²)

Table 12
Predicted Modulus for PCC Pavement

Load lb	Predicted Modulus Values, psi			Abs Sum of % Diff	Subgrade		Subbase θ (bulk)	$E_s = S\sigma_D + I$		Subgrade E for PAVEVAL from Lab Test psi	Subgrade E psi
	E_1	E_2	E_3		σ_V	$\sigma_T \approx \sigma_N$	σ_D	Slope S	Inter I		
5000	4,000,000	81,873	13,145	11.1487	1.195	0.07143	1.1236				
7000	4,000,000	78,787	13,082	6.6225	1.678	0.1022	1.5758	-139	13,302	12,607	7,530

Note: 1 lbf = 4.448 N; 1 psi = 703 kg/m².

NONDESTRUCTIVE EVALUATION PROCEDURE

GENERAL

The procedure outlined in this section is for both rigid and flexible pavements and is based on a layered elastic model that characterizes multilayered pavement systems. The layer strength parameters are computed from field in situ measurements. The strength parameters will be input into an evaluation program that is designed to handle multiwheel aircraft at varying traffic levels. The output will be computed as the allowable load for a 20-year design life pavement. The evaluation will be valid for conditions existing at the time of test and will not account for changes due to such factors as frost action or moisture in the subgrade. These factors should be accounted for through conventional procedures.

NONDESTRUCTIVE TESTING EQUIPMENT

The need for a device with variable loading characteristics is required to describe the nonlinear characteristics of the subgrade material. Laboratory resilient modulus tests would be required to describe these nonlinear characteristics when the description cannot be derived from the NDT data.

The NDT device must output a minimum of three deflections of which one is measured near the applied load and the others are spaced to a distance of at least 36 in. from the applied load. The number of deflection measurements limits the number of variable modulus layers that can be analyzed with this procedure. It is recommended that the magnitude of the first deflection (that deflection measured nearest to the applied load) be at least 0.2 mil.

DATA COLLECTION

PAVEMENT INFORMATION

Before evaluating a light aircraft pavement, information as to pavement types, layer thicknesses, and layer types must be derived from construction records or from destructive tests (cores or test pits). This information is required for the evaluation of allowable load as well as for the determination of NDT locations. If test pits or cores are

required, these tests should be performed after the NDT. Areas of high and low deflections should be included with areas selected through a conventional sampling procedure to identify the causes of these unique NDT responses. Rigid pavement cores or beams should be tested for flexural strength.

The pavement condition should be surveyed to determine the areas and types of distress. It is not within the scope of this procedure to outline a detailed condition analysis. Since material properties are affected by water, frost, and primarily environmental conditions, it may be necessary to reduce the strength parameter for anticipated freeze/thaw conditions, alligator cracking in flexible pavements, and the presence of joints and cracks in rigid pavements.

TEMPERATURE DATA

Temperature data are required for AC pavements to evaluate the pavement properties at the time of testing and the ability of the pavement system to support future operations. The pavement temperature during the time of testing is determined at the mid-depth of the AC layer, the pavement surface, ambient temperature, and the previous five-day mean air temperature from Figure 22.¹³ The pavement surface temperature should be measured at one-hour intervals during the period of testing. The mean air temperature can be obtained from the nearest office of the National Oceanographic and Atmospheric Administration.

To evaluate the pavement system for future operations, the average daily maximum temperature and average daily mean temperature is needed for the hottest months and the spring thaw months. These data can also be obtained from the nearest office of the National Oceanographic and Atmospheric Administration.

NDT TEST DATA

NDT should be conducted at 100-ft intervals alternating to either side of the center line in the wheelpaths on flexible pavements. Rigid pavement tests should be conducted in the slab center also alternating to either side of the feature center line. A minimum of five tests should be conducted in each pavement type. Parking aprons should be

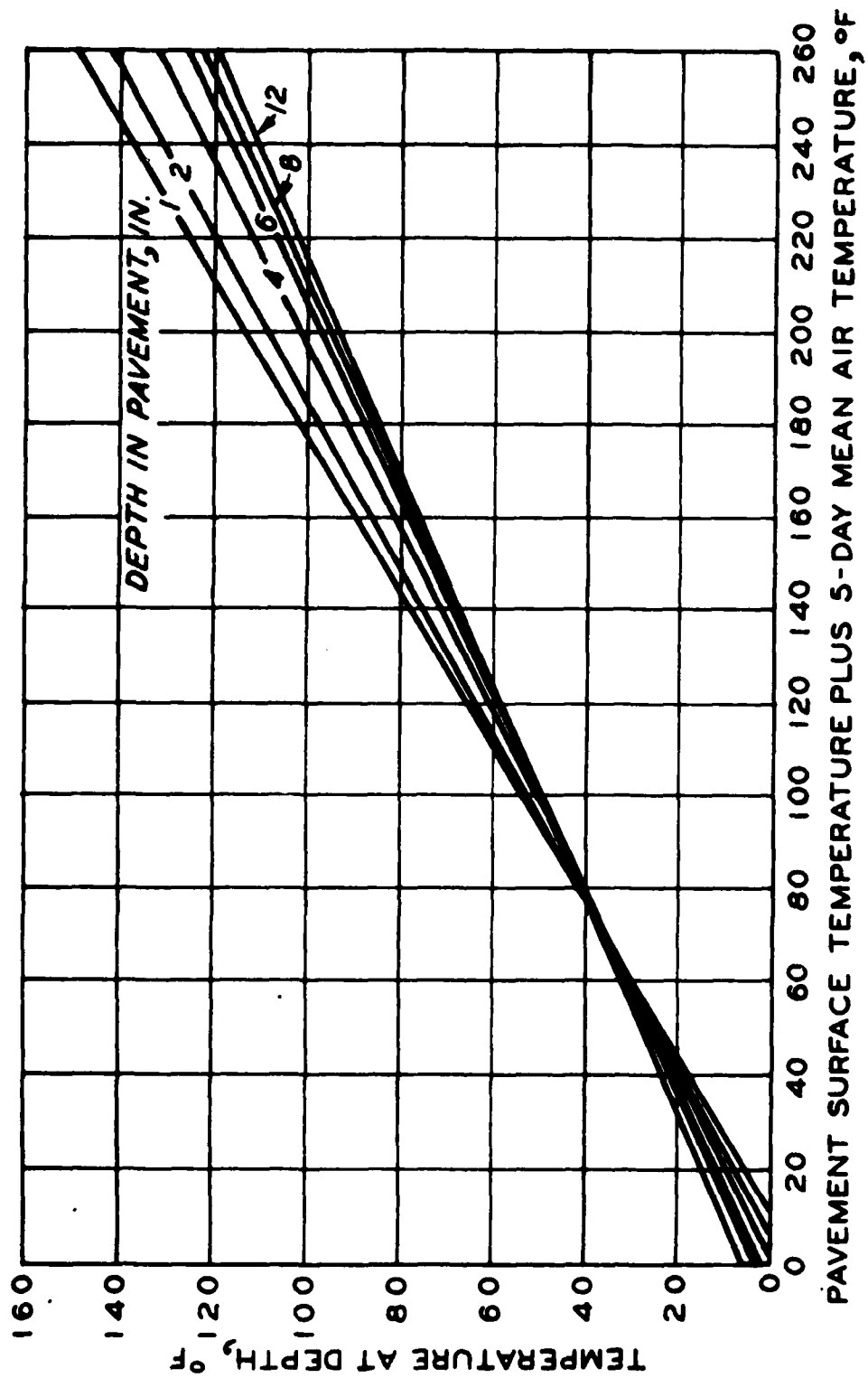


Figure 22. Prediction of flexible pavement temperatures ($1^{\circ}\text{F} = -17^{\circ}\text{C}$)

tested on a 200-ft grid system. Testing should not be conducted when the pavement or subgrade is frozen.

The NDT device should be operated at the frequency that produces the best signal response. For the Model 2008 Road Rater, this frequency is 15 Hz. Deflection basin data should be collected at the maximum force output of the device and at a force level of 50 to 75 percent of the maximum force output.

DETERMINATION OF LAYER MODULUS VALUES

The CHEVDEF program provides a tool with which the modulus values of up to four layers can be predicted. The CHEVDEF program input guide, typical input, and program listing are furnished in Appendix B. Sensitivity studies presented earlier in this report showed that the moduli of the subgrade and other lower layers in the pavement system reproduce well even when the surface moduli may differ. Also since the model assumes a uniform pressure and the Model 2008 Road Rater applies a rigid plate to the pavement, it is recommended that the modulus values of the surface layer be assigned as described below.

For flexible pavements, the modulus of the AC should be determined from Figure 3. The pavement temperature can be computed from the surface temperature plus the previous five-day mean air temperature (Figure 22). The depth should be the midpoint of the AC thickness.

Table 13 gives approximate ranges for the modulus of the pavement materials. These ranges represent very broad limits that should be compressed for the CHEVDEF program. For example, if a pavement with a cement-stabilized base is evaluated and the traffic history indicates very little heavy traffic has been applied, a range for the stabilized base should be selected between 600,000 and 1,500,000 psi.

NDT results should be analyzed by plotting the number one sensor deflection versus the distance along the feature. Pavement areas should be divided according to pavement types and pavement deflections. For each area, each deflection of the basin should be averaged to determine the mean deflection basin.

$$\frac{\sum D_1}{n} = \overline{D_1} ; \frac{\sum D_2}{n} = \overline{D_2} ; \text{etc.}$$

where

- D_1 = deflection from number one sensor
 n = number of tests in particular items
 \bar{D} = deflection to be used for evaluation

The mean deflection values for each pavement area should be input to CHEVDEF in mils.

Table 13
Typical Ranges for Modulus Estimates
and Poisson's Ratio Values for Pavement Layers

<u>Material</u>	<u>Range of Modulus</u> <u>10^3 psi</u>	<u>Assigned Value</u> <u>of Poisson's Ratio</u>
*AC	100 - 1000	0.35
PCC	4000 - 6000	0.15
Untreated base	2 - 160	0.35
Treated base	8 - 2000	0.35
Subgrade	2 - 37	0.4

Note: 1 psi = 703 kg/m².

* Temperature- and frequency-dependent.

In analyzing the results from the CHEVDEF program, it is important to check the predicted modulus for a layer against the limit. If the modulus does hit a limit, the program should be rerun modifying the limits to include the predicted E disregarding boundary conditions (see Appendix B, Example Output).

The highest load should be evaluated first with the CHEVDEF. The values for the modulus for the upper layers obtained from this run may be used for constant values when running the lower load to determine the relationship of stress versus modulus for the subgrade. For example, if the pavement contains three layers, consisting of AC, granular base, and subgrade, the modulus for the AC and granular layer as determined from the initial run of the high load should be held constant at the values for the run at the lower load.

Once the modulus values and deviator stress are obtained, the following equations are used to describe the nonlinearity of the subgrade:

$$S = \frac{E_1 - E_2}{\sigma_{D7} - \sigma_{D5}}$$

and

$$I = E_1 - S\sigma_{D7}$$

where

S = slope

E₁ = predicted modulus for high load (7000 lb for 2008 Road Rater)

E₂ = predicted modulus for low load (5000 lb for 2008 Road Rater)

σ_{D7} = deviator stress (vertical - radial stress) for 7000-lb load

σ_{D5} = deviator stress (vertical - radial stress) for 5000-lb load

I = intercept

After determining the S and I for the equation above, calculate the limiting strain for AC pavement from Figure 17 based on the design life of the pavement, and compute the design subgrade modulus from the equation given below:

$$E = \frac{I}{1 - S\epsilon}$$

where

E = design subgrade modulus, psi

ε = limiting strain

For rigid pavements, the design subgrade modulus will be selected at a deviator stress of 5 psi, or

$$E = 5S + I$$

DETERMINATION OF ALLOWABLE AIRCRAFT LOADS

The PAVEVAL program presented by Weiss³ will be used to predict allowable aircraft loads. Example inputs for both rigid and flexible pavements are shown in Appendix C. Aircraft characteristics¹⁶ for light aircraft pavements are:

Type	Gross Max/Load kips	Departure to Coverage Ratio	Contact Area sq in.	Wheel Spacing, in.
Single	20	7.94	127	--
Dual	30	5.2	75	18

Note: 1 kip = 4.448 kN; 1 sq in. = 6.45 sq cm; 1 in. = 2.54 cm.

The modulus for the AC surface layer should be determined based on a design pavement temperature for input to Figure 3. The method of selecting the design pavement temperature for this evaluation is taken from Brabston et al.¹⁷ Witczak¹⁸ presents a relationship between pavement temperature and air temperature (Figure 23) that can be used to determine the design pavement temperature if the corresponding design air temperature is known. For this design procedure, the design air temperature for a particular locale is determined by averaging the average daily maximum

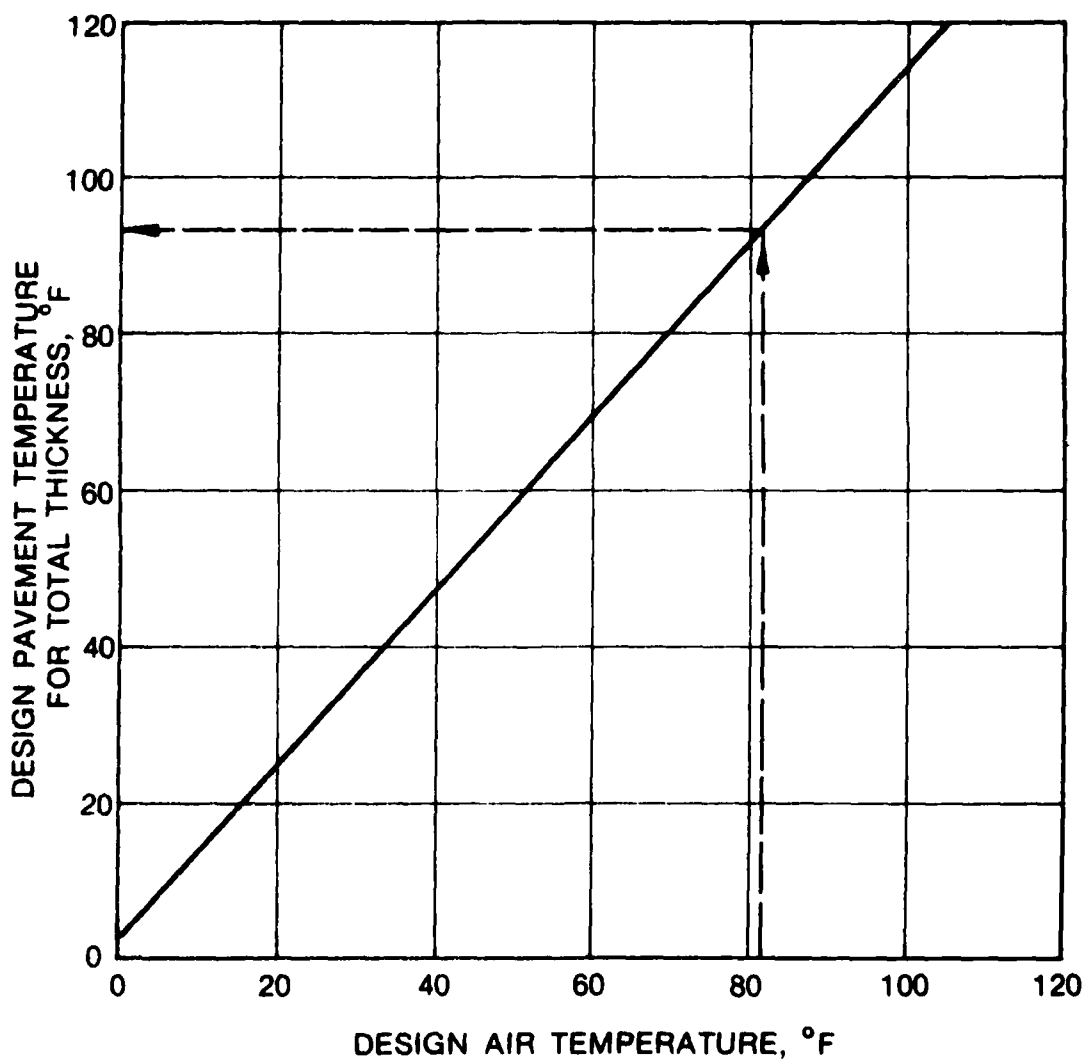


Figure 23. Relationship between design pavement temperature and design air temperature ($1^{\circ}\text{F} = -17^{\circ}\text{C}$)

temperature and the average daily mean temperature for the design month. Generally, the set of average temperatures will be necessary only for the hottest month indicated in the reporting period.

This method of calculating a design modulus for the AC layer is conservative. Other procedures have been reported by Barker and Brabston¹⁴ and Koole.⁶ Modulus values of those layers of base and subbase should be selected from the CHEVDEF output for the high-load (7000-lb) data. These values approximate the stress of the light aircraft and should be representative for the behavior when an elastic model is used.

The PAVEVAL program has the capability of calculating AC and PCC overlays. These procedures are available in the Weiss³ report but were not evaluated for use in light aircraft pavement design as a part of this study. The computer program listed in Appendix B may be reproduced for use by any interested party.

CONCLUSIONS AND RECOMMENDATIONS

This study has resulted in the development of an evaluation procedure for light aircraft pavements based on a layered elastic model. Nondestructive pavement test results are used to predict the layer strength parameters that can be input into a layered elastic model to predict the allowable load-carrying capacities of both rigid and flexible pavements containing either stabilized or nonstabilized layers.

The deflection basins measured from the NDT device at two force levels are used for input to a system that predicts the nonlinear stress-dependent behavior of the subgrade material. Results compare favorably with laboratory resilient modulus tests.

It is recommended that this procedure be adopted for use in evaluating light aircraft pavements. Further study should be conducted to make this approach applicable to air carrier airport pavements. The use of a finite element code for the modeling of a rigid plate and the nonlinear behavior of the granular materials should be included in future studies.

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APPENDIX A: LABORATORY PROCEDURE FOR DETERMINING
THE RESILIENT MODULUS OF SUBGRADE SOILS*

The objective of this test procedure is to determine a modulus value for subgrade soils by means of resilient triaxial techniques. The test is similar to a standard triaxial compression test, the primary exception being that the deviator stress is applied repetitively and at several stress levels. This procedure allows testing of soil specimens in a repetitive stress state similar to that encountered by a soil in a pavement under a moving wheel load.

DEFINITIONS

The following symbols and terms are used in the description of this procedure:

- a. σ_1 = total axial stress.
- b. σ_3 = total radial stress; i.e., confining pressure in the triaxial test chamber.
- c. $\sigma_d = \sigma_1 - \sigma_3$ = deviator stress; i.e., the repeated axial stress in this procedure.
- d. ϵ_1 = total axial strain due to σ_d .
- e. $M_R = \sigma_d / \epsilon_{R1}$ = resilient modulus.
- f. $\theta = \sigma_1 + 2\sigma_3 = \sigma_d + 3\sigma_3$ = sum of the principal stresses in the triaxial state of stress.
- g. σ_1 / σ_3 = principal stress ratio.
- h. Load duration = time interval over which the specimen is subjected to a deviator stress.
- i. Cycle duration = time interval between successive applications of a deviator stress.

SPECIMENS

Various diameter soil specimens may be used in this test, but the recommended specimen diameter is 2.5 to 3.0 in. or approximately four times maximum aggregate size. The specimen height should be at least twice the diameter. Undisturbed or laboratory molded specimens can be used. Procedures for obtaining undisturbed soil specimens are given in

* This procedure is taken from the report by Barker and Brabston.¹⁴

Engineer Manual 1110-2-1907, "Soil Sampling."¹⁹ Methods for laboratory preparation of molded specimens and for back-pressure saturation of specimens, if required, are presented in EM 1110-2-1906, "Laboratory Soils Testing."²⁰

EQUIPMENT

TRIAXIAL TEST CELL

A triaxial cell suitable for use in resilience testing of soils is shown in Figure A-1. This equipment is similar to most standard cells, with the exceptions of being somewhat larger to facilitate the internally mounted load and deformation measuring equipment and having additional outlets for the electrical leads from the measuring devices. For the type of equipment shown, air or nitrogen is used as the cell fluid.

The external loading source may be any device capable of providing a variable load of fixed cycle and load duration, ranging from simple cam-and-switch control of static weights or air pistons to a closed-loop electrohydraulic system. A load duration of 0.2 sec and a cycle duration of 3 sec have been found to be satisfactory for most applications. A square-wave load form is recommended.

DEFORMATION MEASURING EQUIPMENT

The deformation measuring equipment consists of linear variable differential transducers (LVDT's) attached to the soil specimen by a pair of clamps. Two LVDT's are used for the measurement of axial deformation. The clamps and LVDT's are shown in position on a soil specimen in Figure A-1. Details of the clamps are shown in Figure A-2. Load is measured by placing a load cell between the specimen cap and the loading piston as shown in Figure A-1.

Use of the type of measuring equipment described above offers several advantages:

- a. It is not necessary to reference deformations to the equipment, which deforms during loading.
- b. The effect of end-cap restraint on soil response is virtually eliminated.

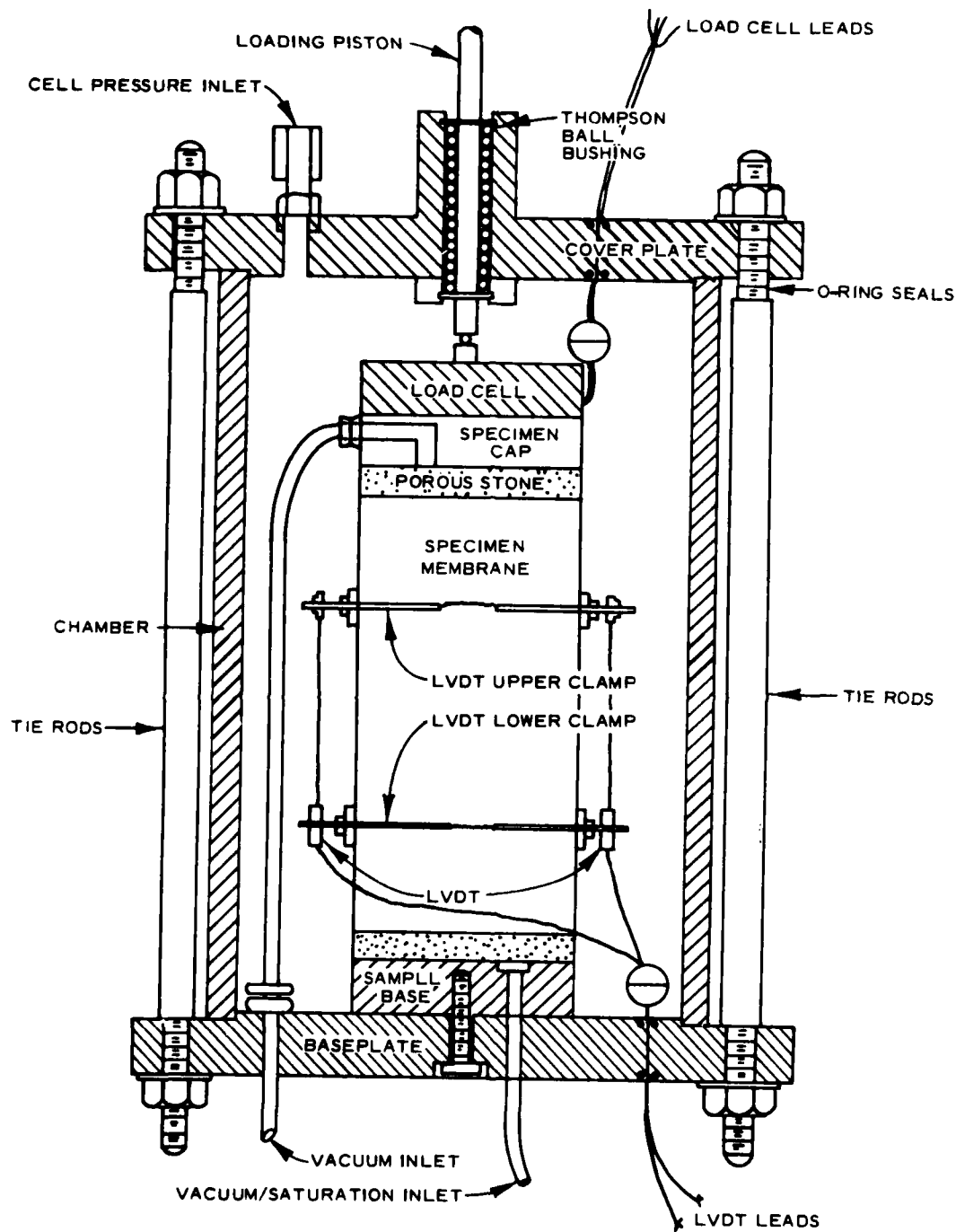
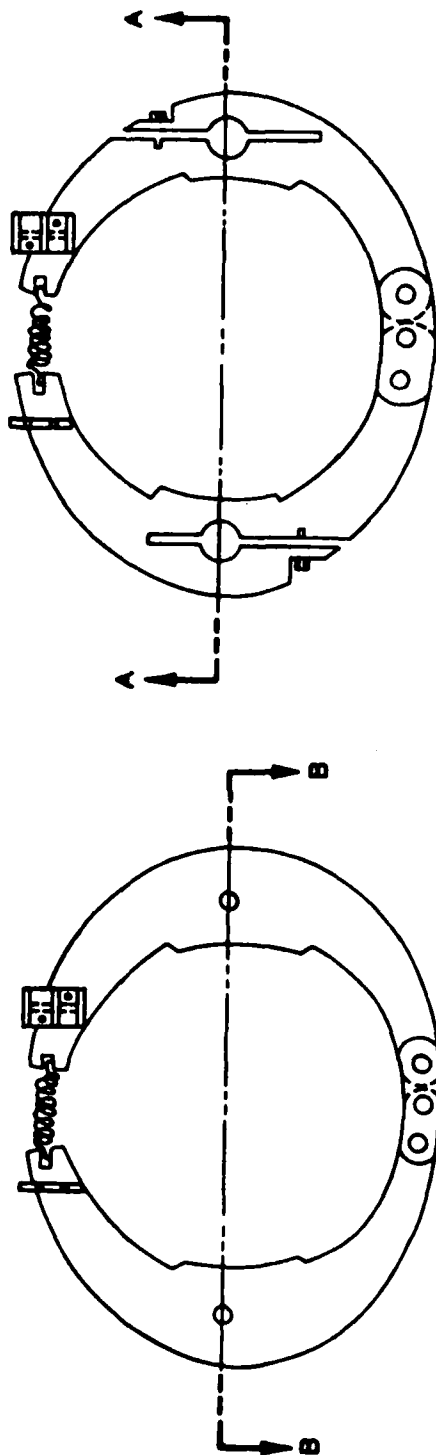


Figure A-1. Triaxial cell



b. LOWER CLAMP



a. UPPER CLAMP

Figure A-2. LVDT clamps

- c. Any effects of piston friction are eliminated by measuring loads inside the triaxial cell.

In addition to the measuring devices, it is also necessary to maintain suitable recording equipment. It is desirable to have simultaneous recording of load and deformation. The number of recording channels can be reduced by wiring the leads from the LVDT's so that only the average signal from each pair is recorded. The introduction of switching and balancing units permits use of a single-chamber recorder. However, this will not permit simultaneous recording.

ADDITIONAL EQUIPMENT

In addition to the equipment described above, the following items are also used:

- a. A 10- to 30-ton-capacity loading machine.
- b. Calipers, a micrometer gage, and a steel rule (calibrated to 0.01 in.).
- c. Rubber membranes, 0.01 to 0.025 in. thick.
- d. Rubber o-rings.
- e. A vacuum source with a bubble chamber and regulator.
- f. A back-pressure chamber with pressure transducers.
- g. A membrane stretcher.
- h. Porous stones.

PREPARATION OF SPECIMENS AND PLACEMENT IN TRIAXIAL CELL

The following procedure should be followed in preparing and placing specimens:

- a. In accordance with procedures specified in EM 1110-2-1906,²⁰ prepare the specimen and place it on the base-plate complete with porous stones, cap, and base and equipped with a rubber membrane secured with O-rings. Check for leakage. If back-pressure saturation is anticipated for cohesive soils, procedures indicated in Appendix X to EM 1110-2-1906 for the Q-type triaxial tests should be followed. For purely non-cohesive soils, it will be necessary to maintain the vacuum during placement of the LVDT's. The specimen is now ready to receive the LVDT's.
- b. Extend the lower LVDT clamp and slide it carefully down over the specimen to approximately the lower quarter point of the specimen.
- c. Repeat this step for the upper clamp, placing it at the upper quarter point. Insure that both clamps lie in horizontal planes.

- d. Connect the LVDT's to the recording unit, and balance the recording bridges. This step will require recorder adjustments and adjustment of the LVDT stems. When a recording bridge balance has been obtained, determine (to the nearest 0.01 in.) the vertical spacing between the LVDT clamps and record this value.
- e. Place the triaxial chamber in position. Set the load cell in place on the specimen.
- f. Place the cover plate on the chamber. Insert the loading piston, and obtain a firm connection with the load cell.
- g. Tighten the tie rods firmly.
- h. Slide the assembled apparatus into position under the axial loading device. Bring the loading device to a position in which it nearly contacts the loading piston.
- i. If the specimen is to be back-pressure saturated, proceed in accordance with EM 1110-2-1906.
- j. After saturation has been completed, rebalance the recorder bridge to the load cell and LVDT's.

RESILIENCE TESTING OF COHESIVE SOILS

The resilient properties of cohesive soils are only slightly affected by the magnitude of the confining pressure σ_3 . For most applications, this effect can be disregarded. When back-pressure saturation is not used, the confining pressure used should approximate the expected in situ horizontal stresses, which will generally be on the order of 1 to 5 psi. A chamber pressure of 2 psi is a reasonable value for most testing. If back-pressure saturation is used, the chamber pressure will depend on the required saturation pressure.

Resilient properties are highly dependent on the magnitude of the deviator stress σ_d . It is therefore necessary to conduct the tests for a range in deviator stress values. The following procedure should be followed:

- a. If back-pressure saturation is not used, connect the chamber pressure supply line and apply the confining pressure (equal to the chamber pressure). If back-pressure saturation is used, the chamber pressure will already have been established.
- b. Rebalance the recording bridges for the LVDT's, and balance the load cell recording bridge.
- c. Begin the test by applying 1000 repetitions of a deviator stress of not more than one-half the unconfined compressive strength.

- d. Decrease the deviator load to the lowest value to be used. Apply 200 repetitions of load, recording the recovered vertical deformation at or near the last repetition.
- e. Increase the deviator load, recording deformations as in Step d. Repeat over the range of deviator stresses to be used. It is recommended that 3, 5, 7, 12, 15, 17, 20, 22, and 25 psi be used.
- f. At the completion of the loading, reduce the chamber pressure to zero. Remove the chamber LVDT's and load cell. Use the entire specimen for the purpose of determining the moisture content.

The results of the resilience tests can be presented graphically as shown in Figure A-3 for the resilient modulus and in the form of a summary table such as Table A-1.

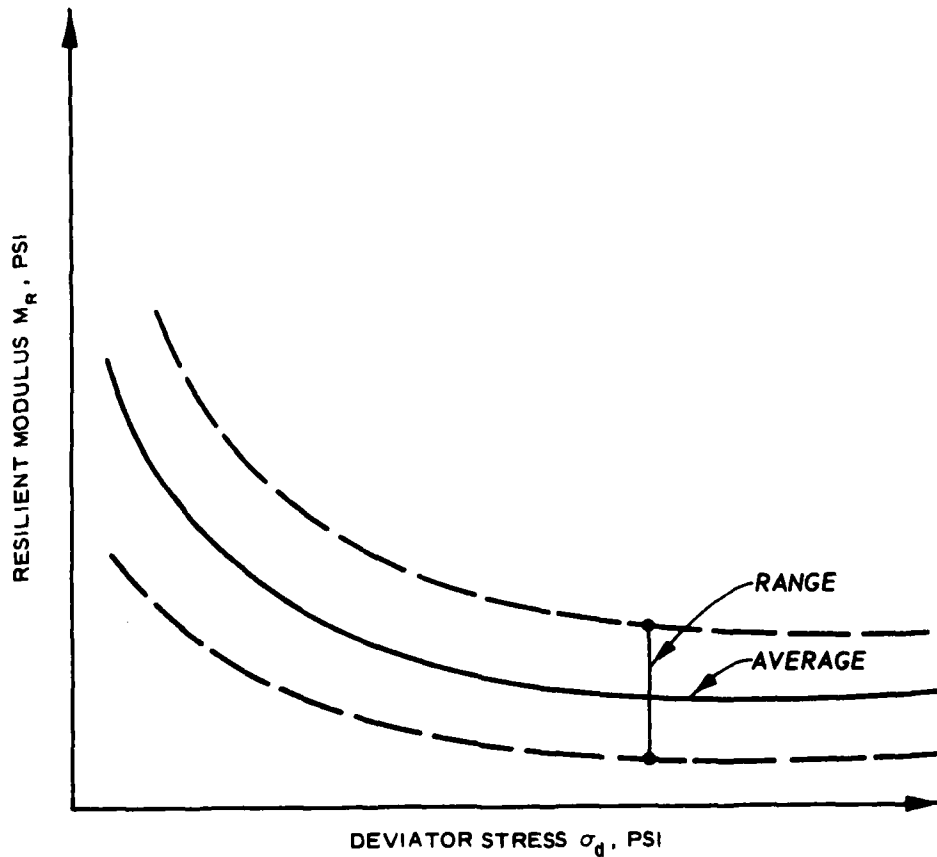


Figure A-3. Presentation of results of resilience tests on cohesive soils (1 psi = 703 kg/m²)

Example Data Form for Recording Results of Resilience Tests of Cohesive Soils

Soil Sample	Soil Specimen Weight	Date
Location	Initial Wt. of Container	Compaction Method
Sample No.	+ Wet Soil - gas	Vertical Spacing Between
Specific Gravity	Final Wt. of Container	LVDI Clamps - inch
	+ Wet Soil - gas	Chamber Pressure - psi
	Wt. Wet Soil Used	Constants
Soil Specimen Measurements	Soil Specimen Volume	Vertical LVDI
Top	Initial Area A_0	
Diameter Middle	in (inch) ²	
Diameter Bottom	Volume $A_0 l_0$	
Average	in (inch) ³	
Membrane Thickness	Wet Density - pcf	Load Cell
Net Diameter	Water Content - %	
Ht. Specimen	% Saturation	Comments
Ht. Cap + Base	Dry Density - pcf	
Initial Length L_0		

[illegible]

Note: 1 in. = 2.54 cm; 1 in.² = 6.45 cm²; 1 in.³ = 16.39 cm³; 1 pcf = 16.02 kg/m³;
1 psi = 703 kg/m²

RESILIENCE TESTING OF COHESIONLESS SOILS

The resilient modulus of cohesionless soils M_R is dependent upon the magnitude of the confining pressure σ_3 and is nearly independent of the magnitude of the repeated axial stress. Therefore, it is necessary to test cohesionless materials over a range of confining and axial stresses. (The confining pressure is equal to the chamber pressure less the back pressure for saturated specimens.) The following procedures should be used for this type of test:

- a. Use confining pressures of 5, 10, 15, and 20 psi. At each confining pressure, test at five values of the principal stress difference corresponding to multiples (1, 2, 3, 5) of cell pressure.
- b. Before beginning to record deformations, apply a series of conditioning stresses to the material to eliminate initial loading effects. The greatest amount of volume change occurs during the application of the conditioning stresses. Simulation of field conditions suggests that drainage of saturated specimens should be permitted during the application of these loads but that the test loading (beginning in Step f below) should be conducted in an undrained state.
- c. Set the axial load generator to apply a deviator stress of 10 psi (i.e., a stress ratio equal to 3). Activate the load generator and apply 200 repetitions of this load. Stop the loading.
- d. Set the axial load generator to apply a deviator stress of 20 psi (i.e., a stress ratio equal to 3). Activate the load generator and apply 200 repetitions of this load. Stop the loading.
- e. Repeat as in Step d above maintaining a stress ratio equal to 6 and using the following order and magnitude of confining pressures: 10, 20, 10, 5, 3, and 1 psi.
- f. Begin the record test using a confining pressure of 1 psi and an equal value of deviator stress. Record the resilient deformation after 200 repetitions. Increase the deviator stress to twice the confining pressure and record the resilient deformation after 200 repetitions. Repeat until a deviator stress of 5 times the confining pressure is reached (stress ratio of 6).
- g. Repeat as in Step f above for each value of confining pressure.
- h. When the test is completed, decrease the back pressure to zero, reduce the chamber pressure to zero, and dismantle the cell. Remove the LVDT clamps, etc. Remove the soil specimen, and use the entire amount of soil to determine the moisture content.

Test results should be presented in the form of a plot of $\log M_R$ versus \log of the sum of the principal stresses as shown in Figure A-4. Calculations can be performed using the tabular arrangement shown in Table A-2.

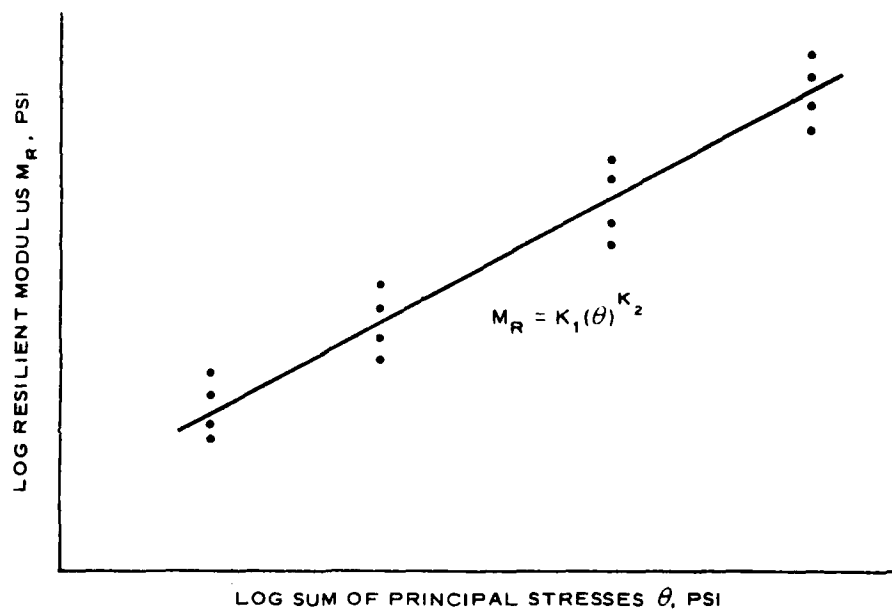


Figure A-4. Presentation of results of resilience tests on cohesionless soils (1 psi = 703 kg/m²)

Example Date Form for Recording Results

of Resilience Tests of Cohesionless Soils

<u>Soil Sample</u>	<u>Initial Wt. of Container</u>	<u>Soil Specimen Weight</u>	<u>Date</u>
<u>Location</u>	+ Wet Soil - gms		<u>Compaction Method</u>
<u>Sample No.</u>	<u>Final Wt. of Container</u>		
<u>Specific Gravity</u>	+ Wet Soil - gms		<u>Vertical Spacing Between LVDT Clamps - inch</u>
	<u>Wt. Wet Soil Used</u>		<u>Constants</u>
<u>Soil Specimen Measurements</u>	<u>Soil Specimen Volume</u>		<u>Vertical LVDT</u>
<u>Top</u>	<u>Initial Area A₀</u>		
<u>Middle</u>	in (inch) ²		
<u>Diameter Bottom</u>	<u>Volume A₀h₀</u>		
<u>Average</u>	in (inch) ²		
<u>Membrane Thickness</u>	<u>Wet Density pcf</u>		<u>Load Cell</u>
<u>Net Diameter</u>	<u>Water Content - %</u>		
<u>Wt. Specimen + Cap + Base</u>	<u>% Saturation</u>		<u>Comments</u>
<u>Wt. Cap + Base</u>	<u>Dry Density - pcf</u>		
<u>Initial Length L₀</u>	<u>Void Ratio</u>		

[illegible]

Note: 1 in. = 2.54 cm; 1 in.² = 6.45 cm²; 1 in.³ = 16.39 cm³; 1 pcf = 16.02 kg/m³; 1 psi = 703 kg/m²

APPENDIX B: CHEVDEF PROGRAM

INTRODUCTION

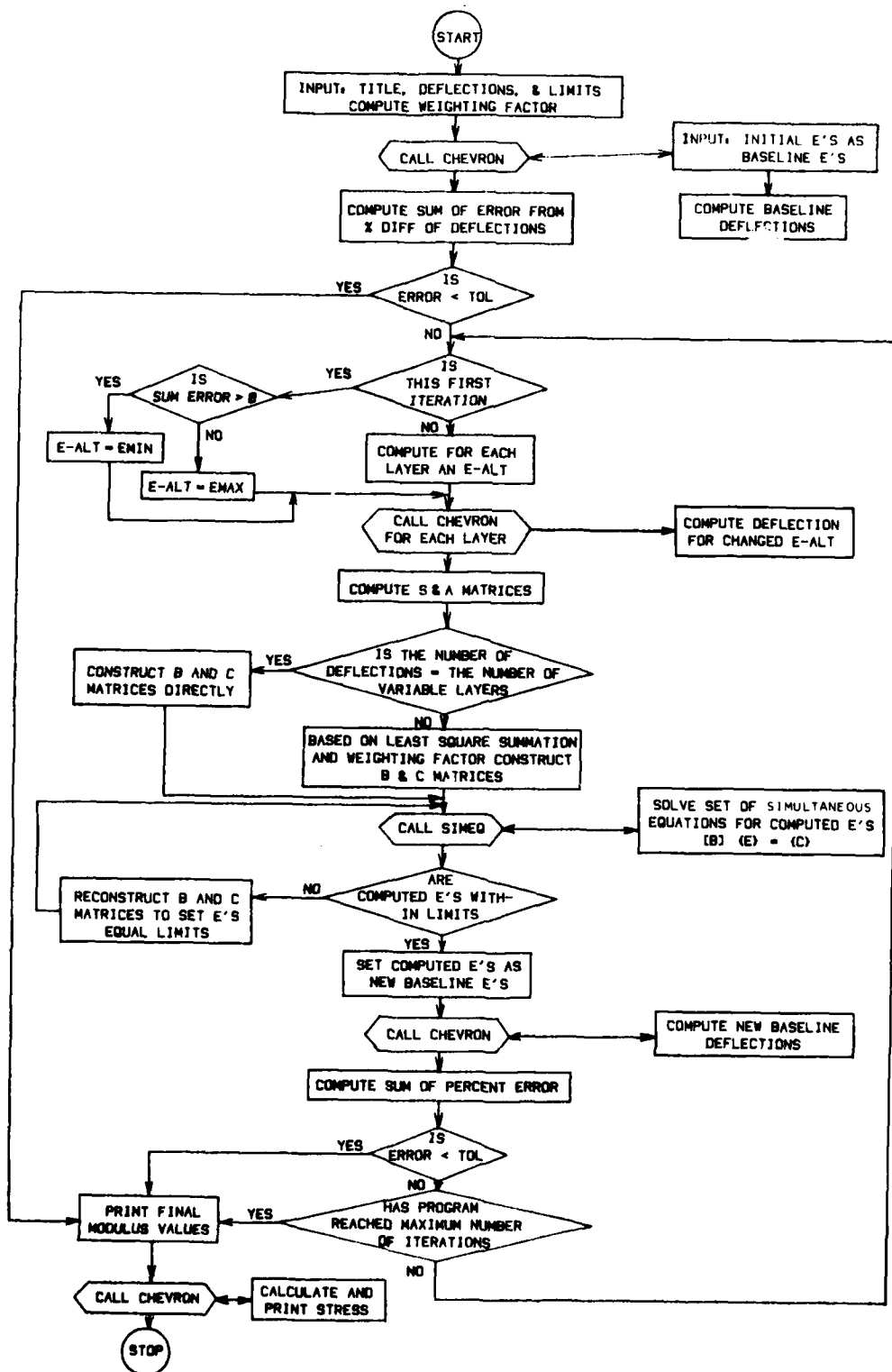
The CHEVDEF program takes measured deflections from a deflection basin with initial estimates and ranges of layer modulus and computes the modulus values that best describe the input deflection basin. A linearly layered elastic computer program originally developed by Chevron Oil Company is used as a subroutine to calculate the stress, strains, and deflections.

The information provided herein is as follows:

- a. Flowchart.
- b. Input guide.
- c. Example input.
- d. Example output.
- e. Program listing.

FLOWCHART

A flowchart describing the logic of the program is presented on the following page.



INPUT GUIDE

PROGRAM CHEVDEF (Matching of Pavement Deflections Using CHEVRON Layered Elastic Computer Program)

Line 1

LINENU	NPROB
--------	-------

NPROB = Number of data sets

Line 2

Title	72 characters
-------	---------------

Note: Line 2 through Line 13 are repeated for each data set.

Line 3

LINENU	ND	RRD(1)	--	--	RRD(ND)
--------	----	--------	----	----	---------

ND = Number of deflection readings (maximum of 4)

RRD(i) i = 1, ND = Measured deflections in mils

Line 4

LINENU	NL	TOL	MAXIT
--------	----	-----	-------

NL = Number of variable layers for which the modulus is to be determined (not to exceed the number of deflections)

TOL = Tolerance in percent for stopping programs (usually = 10)

MAXIT = Maximum number of iterations (usually = 3)

Line 5-1 through 5-NL (one line for each unknown modulus)

LINENU	ILV(i)	EMIN(i)	EMAX(i)
--------	--------	---------	---------

ILV(i) = System layer number for unknown modulus value i

EMIN(i) = Minimum allowable modulus for unknown modulus i

EMAX(i) = Maximum allowable modulus for unknown modulus

Line 6

Title at start of CHEVRON data	72 characters
--------------------------------	---------------

Line 7

LINENU	WGT	PSI	NOUTP	NPUN
--------	-----	-----	-------	------

WGT = Total load applied to pavement

PSI = Contact pressure of load

NOUTP = Control output : set = 0

NPUN = Control output : set = 1

Line 8 (continue to additional lines as necessary for all E's and V's)

LINENU	NS	E(i)	V(i)	--	--	E(NS)	V(NS)
--------	----	------	------	----	----	-------	-------

NS = Total number of layers in system

E(i) = Starting modulus for layers i = 1, NS

V(i) = Poisson's ratio for layers i = 1, NS

Line 9

LINENU	HH(1)	HH(2)	--	--	HH(NS-1)
--------	-------	-------	----	----	----------

HH(i) = Thickness of layer i = 1, NS-1

Line 10

LINENU	iR	RR(1)	RR(2)	--	RR(iR)
--------	----	-------	-------	----	--------

iR = Number of radial offsets (set = ND)

RR(i) i = 1, iR = Distance to deflection readings

Line 11

LINENU	iZ	ZZ(1)
--------	----	-------

iZ = Number of depth set = 1

ZZ(1) = Depth of deflection set = 0

Note: After determination of final modulus subgrade, CHEVRON is called for computation of stress, strains, and deflection at selected points. These soils should be the center of granular layers and the top of the subgrade material.

Line 12

LINENU	iR	RR(1)	RR(2)	--	RR(iR)	/
--------	----	-------	-------	----	--------	---

iR = Number of offsets (if iR = 0 returns for new data set)

RR(i) i = 1, iR = Distance to selected points

Line 13

LINENU	iZ	ZZ(1)	ZZ(2)	--	RR(iZ)	/
--------	----	-------	-------	----	--------	---

iZ = Number of depth

ZZ(i) i = 1, iZ = Depth to selected points

Note: Run is now terminated or returned for new data.
For devices with two loaded areas, use total force
on one area and compute radial distances for Line 10.

EXAMPLE INPUT

An example input for the PTRF 1A item is listed below. Control cards preceeding input are for the Honeywell G635 Computer in the remote batch mode (CARDIN).

```

010**N( )
020%IDENT:R0SF300,CURTIS
030%OPTION:F0RTRAN
040%USE!.GTLIT
050%FORTY:XREF
060%SELECTA:R0SF300/CHEVDEF
070%EXECUTE
080%LIMITS:40,30K,,6K
090 010 1
100 020PTRF 1A RR2008 DEFL. (7000 LB)
110 030 4,5.908,4.433,3.067,1.933
120 040 3,10,3
130 050 1,20000,700000
140 060 2,20000,100000
150 070 3,10000,30000
160 080 CHEVRON
170 090 7000,27.508,0,1
180 100 4,500000,0.35,50000,0.35,20000,0.4,1000000,0.5
190 110 7.5,20.5,212
200 120 4,4.5,12,24,36
210 130 1,0
220 140 1,0
230 150 2,7.5,28
240%ENDJOB

```

EXAMPLE OUTPUT

An example output for the PTRF 1A item is provided on the following pages. The number of problems to be solved is 1.

020 PTRF 1A RR2008 DEFL. (7000 LB.)

NUMBER OF VARIABLE LAYERS AND TARGET DEFLECTIONS = 3

	DEFLECTION READINGS IN MILS			
POSITION NO:	1	2	3	4
DEFLECTIONS:	5.908	4.433	3.067	1.933
WEIGHTING FACTOR:	0.169	0.226	0.326	0.517

VARIABLE LAYER NO	SYSTEM LAYER NO	VALUE OF MAXIMUM MODULUS	VALUE OF MINIMUM MODULUS	US
1	1	700000.0	20000.0	
2	2	100000.0	20000.0	
3	3	30000.0	10000.0	

*****080 START DATA FOR CHEVRON

THE PROBLEM PARAMETERS ARE

TOTAL LOAD..	7000.00	LBS
TIRE PRESSURE..	27.51	PSI
LOAD RADIUS..	9.00	IN.

LAYER NO.	MODULUS	POISSONS RATIO	THICKNESS
1	500000.	0.350	7.50
2	50000.	0.350	20.50
3	20000.	0.400	212.00
4	1000000.	0.500	SEMI-INFINITE

POSITION	DEFLECTION	MEASURED	DIFFERENCE	% DIFF.
1	5.5500	5.9080	0.3580	6.1
2	4.2409	4.4330	0.1921	4.3
3	2.8706	3.0670	0.1964	6.4
4	2.0131	1.9330	-0.0801	-4.1
		ABSOLUTE SUM:	0.8265	20.9390
		ARITHMETIC SUM:		12.6527

DATA FOR DEVELOPING EQUATION: FOR ITERATION: NO. 1

LAYER NO.	INITIAL MODULUS	CHANGED MODULUS	OFFSET DISC.	DEFLECTION: INITIAL	CHANGED	PERDIN
61						
1	500000.	20000.	4.50	5.550	14.501	5.908
			12.00	4.241	5.428	4.433
			24.00	2.871	3.023	3.067
			36.00	2.013	2.102	1.933
2	50000.	20000.	4.50	5.550	7.686	5.908
			12.00	4.241	5.981	4.433
			24.00	2.871	3.808	3.067
			36.00	2.013	2.391	1.933
3	20000.	10000.	4.50	5.550	7.507	5.908
			12.00	4.241	6.037	4.433
			24.00	2.871	4.609	3.067
			36.00	2.013	3.542	1.933

PREDICTED E DISREGARDING BOUNDARY CONDITIONS
500060. 40304. 21130.

POSITION	DEFLECTION	MEASURED	DIFFERENCE	% DIFF.
1	5.8718	5.9080	0.0362	0.6
2	4.4794	4.4330	-0.0464	-1.0
3	2.9416	3.0670	0.1254	4.1
4	1.9892	1.9330	-0.0562	-2.9
		ABSOLUTE SUM:	0.2642	8.6555
		ARITHMETIC SUM:		0.7480
		AVERAGE:	0.0661	2.1639

THE FINAL MODULUS VALUES ARE

	500060.	40304.	21130.	1000000.		
	DEFLECTIONS ARE IN TOLERANCE					
R	Z	VERTICAL	TANGENTIAL	RADIAL	SHEAR	BULK
0.	-7.5	STRE -9.397E 00	4.723E 01	4.723E 01	0.	8.507E 01
		STRA -8.491E-05	6.797E-05	6.797E-05	0.	5.103E-05
		DSPL 5.909E-03				
0.	7.5	STRE -9.397E 00	-8.452E-01	-8.452E-01	0.	-1.109E 01
		STRA -2.185E-04	6.797E-05	6.797E-05	0.	-8.253E-05
		DSPL 5.909E-03				
0.	-28.0	STRE -2.019E 00	1.313E 00	1.313E 00	0.	6.064E-01
		STRA -7.291E-05	3.871E-05	3.871E-05	0.	4.514E-06
		DSPL 3.439E-03				
0.	28.0	STRE -2.019E 00	1.701E-02	1.701E-02	0.	-1.985E 00
		STRA -9.621E-05	3.871E-05	3.871E-05	0.	-1.879E-05
		DSPL 3.439E-03				
***** END OF PROGRAM *****						

PROGRAM LISTING

HIT SERIES 600 ON 11 10 20 AT 12:55 CHANNEL 6007

SYSTEM REPORT
OLD OR NEW-OLD CHEVDEF
OLD OR NEW-OLD
OLD FILE CHEVDEF
READY
•LIST

```

000100 .....
000200 .....
000300 .....
000400 .....
000500 .....
000600 .....
000700 .....
000800 .....
000900 .....
001000 .....
001100 .....
001200 .....
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001600 .....
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002100 .....
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004300 .....
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004500 .....
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004700 .....
004800 .....
004900 .....
005000 .....
005100 .....
005200 .....
005300 .....
005400 .....

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THIS PROGRAM CONTAINS AN ITERATIVE PROCEDURE TO CALCULATE
 MODULUS VALUES FOR UP TO 4 PAVEMENT LAYERS FROM THE DEFLECTION
 BASIN MEASUREMENTS. THE PROGRAM USES THE CHEVRON N - LAYER
 ELASTIC SYSTEMS PROGRAM AS A SUBROUTINE TO CALCULATE DEFLECTIONS
 FROM INITIAL AND ITERATIVE MODULUS VALUES.

PROGRAM NAME: CHEVDEF
 CODED BY: DR. WALTER R. BARKER
 POINT OF CONTACT:
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 VICKIBURG, MISSISSIPPI 39180
 COMPUTER: WATERWAYS EXPERIMENT STATION, GE635
 LANGUAGE: FORTRAN IV
 DATE COMPLETED: JULY 1980
 SPECIAL REQUIREMENT: CARDIN; REMOTE BATCH PROCESSING
 STORAGE: DISC

```

      CALL EXOPT(67,1,1,0)
      LOGICAL RECALC,PEITER,CONTIN
      CHARACTER*80 TEXT1
      CHARACTER*4 CONPAR
      CHARACTER IFUN*1,4,4)
      INTEGER COUNT
      DIMENSION EL(4,3),EMAX(4),EMIN(4),,4,4),R(4,4),C(4),B(4,4)
      C(4),R(4), ILV(4),NDF(4),IDF(4,4)
      Z(4,4),ATEMP(10)
      PERL MOIC,NU,CTEMP(4),BTEMP(4,4)
      Z,ETOL(4),DF(4,3), RFD(4),DTOL(4),
      STEFDEF(4),PCT(4),ACCUR(2)
      COMMON OPT,COUNT,DEF(4),NLAY
      COMMON RMCDY,RX1(10),,20(10),,E(5),,V(5),,HH(4),
      H(4),,AC(396),,AR(396,5),,BR(396,5),,CR(396,5),
      D(396,5),,RJ(396),,RJ1(396),,RJ2(396),,RJ3(396),,TITLE(20),
      IE,T(11),,PC(100),,D(5,4,4),,DC(4),,FM(2,2),
      FM(4,4,4),,DUMM7(4)

```

```

00550      DATA CONPAR, N
00560      READ(5,210) LINENU, NPROB
00570      WRITE(6,105) NPROB
00580      DO 9999 NPF=1,NPROB
00590      WRITE(6,1212) NPF
00600 9995 CONTINUE
00610      READ(5,1000) TEXT1
00620      WRITE(6,200) TEXT1
00630      READ(5,210) LINENU,ND,PPD(1),I=1,ND
00640      SUM = 0.
00650      COUNTR=1
00660 1 CONTINUE
00670      ITER=0
00680      READ(5,210) LINENU,NL,TOL,MAXIT
00690      DO 5 I = 1,ND
00700      W(I) = 1./PPD(I)
00710 5 CONTINUE
00720      DO 8 I=1,NL
00730      READ(5,210) LINENU,NW,EMIN(I),EMAX(I)
00740 8 ILV(I)=NW
00750      WRITE(6,600) NL
00760      WRITE(6,619) (I,I=1,ND)
00770      WRITE(6,620) (PPD(I),I=1,ND)
00780      WRITE(6,621) (W(I),I=1,ND)
00790      WRITE(6,790)
00800      WRITE(6,650)
00810      DO 59 MS=1,NL
00820      WRITE(6,660) MS,ILV(MS),EMAX(MS),EMIN(MS)
00830 59 CONTINUE
00840      CALL CHEVRON
00850      WRITE(6,830)
00860      CONTIN = .TRUE.
00870      SUM = 0.
00880      SUMP = 0.0
00890      ASUM=0.0
00900      DO 9 I = 1,ND
00910      ERR = PPD(I)-DEF(I)
00920      PERC=(ERR/PPD(I))*100
00930      SUM = SUM + ABS(ERR)
00940      SUMP = SUMP + ABS(PERC)
00950      ASUM = ASUM+PERC
00960      WRITE(6,820) I,DEF(I),PPD(I),ERR,PERC
00970      DEF(I,3) = DEF(I)
00980 9 CONTINUE
00990      IF (SUMP.GT.TOL) CONTIN = .FALSE.
01000      WRITE(6,840) SUM,SUMP,ASUM
01010      IF (CONTIN) GOTO 89
01020      COUNTR=3
01030 6 ITER=ITER+1
01040      DO 15 I = 1,NL
01050      K = ILV(I)
01060      EL(I,3) = ALOG10(E(K))
01070 15 CONTINUE
01080      WRITE(6,760) ITER
01090      DO 60 JX=1,NL
01100      K=ILV(JX)
01110      IF(ITER.EQ.1)GO TO 21
01120      IF(C(JX).EQ.CTEMP(JX))
01130      CTEMP(JX)=(ALOG10(EMAX(JX))+ALOG10(EMIN(JX)))/2
01140      EL(JX,1)=(3*C(JX)+CTEMP(JX))/4

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01150      IF (ABS (E(K) - EMAX(JX)) .LT. 100 .OR. ABS (E(K) - EMIN(JX)) .LT. 100) GO TO 24
01160      IF (C(JX) .LT. CTEMP(JX)) GO TO 23
01170      IF (ACUM .LT. 0) EL(JX,1) = (3 * C(JX) + ALOG10 * EMAX(JX)) / 4
01180      GO TO 24
01190      23 IF (ACUM .GT. 0) EL(JX,1) = (3 * C(JX) + ALOG10 * EMIN(JX)) / 4
01200      24 E(K) = 10 ** EL(JX,1)
01210      GO TO 40
01220      21 IF (ASUM .LT. 0) GO TO 30
01230      E(K) = EMIN(JX)
01240      GO TO 40
01250      30 E(K) = EMAX(JX)
01260      40 EL(JX,2) = ALOG10 * E(K)
01270      CALL CHEVRON
01280      DO 50 KK = 1,ND
01290      DF(KK,2) = DEF(KK)
01300      45 CONTINUE
01310      C(KK,JX) = (DF(KK,2) - DF(KK,3)) / (EL(JX,2) - EL(JX,3))
01320      A(KK,JX) = DF(KK,2) - EL(JX,2) * S(KK,JX)
01330      50 CONTINUE
01340      ET3 = 10 ** EL(JX,3)
01350      WRITE(6,770) ILV(JX), ET3, E(ILV(JX)), AX1(1), DF(1,3), DEF(1), RPD(1)
01360      IF (ND.EQ.1) GO TO 39
01370      DO 34 JS = 2,ND
01380      WRITE(6,780) AX1(JS), DF(JS,3), DEF(JS), RPD(JS)
01390      34 CONTINUE
01400      39 CONTINUE
01410      WRITE(6,810)
01420      E(K) = 10 ** EL(JX,3)
01430      60 CONTINUE
01440      DO 65 KK = 1,ND
01450      65 CONTINUE
01460      DO 69 KK = 1,ND
01470      69 CONTINUE
01480      IF (NL.NE.ND) GO TO 101
01490      DO 120 I = 1,NL
01500      C(I) = RPD(I) - A(I,NL) - S(I,NL) * EL(NL,3)
01510      DO 110 J = 1,NL
01520      C(I) = C(I) + S(I,J) * EL(J,3)
01530      B(I,J) = S(I,J)
01540      BTEMP(I,J) = B(I,J)
01550      110 CONTINUE
01560      CTEMP(I) = C(I)
01570      120 CONTINUE
01580      GO TO 79
01590      101 CONTINUE
01600      DO 80 I = 1,NL
01610      C(I) = 0.0
01620      DO 70 J = 1,ND
01630      C(I) = C(I) + S(J,I) * (RPD(J) - A(J,NL) - S(J,NL) * EL(NL,3) * OM(J))
01640      DO 67 JS = 1,NL
01650      C(I) = C(I) + S(J,JS) * S(J,I) * EL(JS,3) * OM(J)
01660      67 CONTINUE
01670      70 CONTINUE
01680      DO 68 JS = 1,NL
01690      B(I,JS) = 0.
01700      DO 71 J = 1,ND
01710      B(I,JS) = B(I,JS) + S(J,I) * S(J,JS) * OM(J)
01720      71 CONTINUE
01730      BTEMP(I,JS) = B(I,JS)
01740      68 CONTINUE

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01750      CTEMP(I) = C(I)
01760      80 CONTINUE
01770      79 CONTINUE
01780      DO 78 JN=1,NL
01790      78 CONTINUE
01800      CALL TIMEO(B,C,NL,KEP,4)
01810      WRITE(6,301)
01820      301 FORMAT(1H )
01830      WRITE(6,301)
01840      WRITE(6,302)
01850      302 FORMAT(1H , PREDICTED E DISREGARDING BOUNDARY CONDITIONS )
01860      DO 73 JN=1,NL
01870      ATEMP(JN)=10**C(JN)
01880      73 CONTINUE
01890      WRITE(6,251) (ATEMP(JN),JN=1,NL)
01900      IF(KEP.NE.0)GO TO 80
01910      RECALC=.FALSE.
01920      DO 84 I=1,NL
01930      IF(KEP)GO TO 84
01940      AMAX = ALDGL0*EMAX(I)
01950      AMIN = ALDGL0*EMIN(I)
01960      IF(C(I).GE.(AMIN-.0001).AND.C(I).LE.(AMAX+.0001))GO TO 84
01970      RECALC=.TRUE.
01980      DO 82 K=1,NL
01990      IF(K.EQ.1)GO TO 86
02000      C(K)=CTEMP(K)
02010      86 DO 81 L=1,NL
02020      B(L,K)=BTEMP(L,K)
02030      81 CONTINUE
02040      82 CONTINUE
02050      IF(C(I).LT.AMIN)C(I)=AMIN
02060      IF(C(I).GT.AMAX)C(I)=AMAX
02070      CTEMP(I)=C(I)
02080      DO 83 K=1,NL
02090      B(I,K)=0.0
02100      BTEMP(I,K)=B(I,K)
02110      83 CONTINUE
02120      B(I,I)=1.0
02130      BTEMP(I,I)=B(I,I)
02140      84 CONTINUE
02150      IF(KEP)GO TO 79
02160      DO 85 I=1,NL
02170      J=ILV(I)
02180      TEMP=10**C(I)
02190      TEMP1 = 10**EL(I,3)
02200      ETOL(I)=ABS((TEMP-TEMP1)/TEMP1)*100)
02210      E(I)=TEMP
02220      CTEMP(I)=EL(I,3)
02230      85 CONTINUE
02240      CALL CHEVRON
02250      CUM = 0.
02260      CUMP = 0.0
02270      ACUM = 0.0
02280      CONTIN=.TRUE.
02290      WRITE(6,830)
02300      DO 88 I = 1,ND
02310      ERR = PRD(I)-DEF(I)
02320      PERC=ERR/PRD(I)*100
02330      CUM = CUM + ABS(ERR)
02340      CUMP = CUMP + ABS(PERC)

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02350      WRITE(6,820) I, DEF(I), PRD(I), ERR, PERC
02360      DF(I,3)=DEF(I)
02370      AUM = AUM + PERC
02380 88      CONTINUE
02390      IF (CUMP.GT.TOL) CONTIN=.FALSE.
02400      PERCUM=CUM/ND
02410      PERCUMP=CUMP/ND
02420      WRITE(6,840) SUM, CUMP, AUM
02430      WRITE(6,715) PERSUM, PERCUMP
02440      REITER = .TRUE.
02450      DO 87 I=1,NLAYS
02460      IF (ETOL(I).GT.TOL) REITER=.FALSE.
02470 87 CONTINUE
02480      IF (CONTIN) GO TO 89
02490      IF (REITER) GO TO 89
02500      IF (ITER.LT.MAXIT) GO TO 6
02510      WRITE(6,9000) (E(I), I=1, NLAYS)
02520      WRITE(6,310)
02530      WRITE(6,303)
02540 303 FORMAT(1H, ' REACHED MAX NO OF ITERATIONS')
02550      GO TO 10
02560 89 WRITE(6,9000) (E(I), I=1, NLAYS)
02570      IF (CONTIN) WRITE(6,304)
02580 304 FORMAT(1H, ' DEFLECTIONS ARE IN TOLERANCE')
02590      IF (REITER) WRITE(6,305)
02600 305 FORMAT(1H, ' CHANGE IN MODULUS VALUES ARE IN TOLERANCE')
02610 10 COUNTR=99
02620      CALL CHEVRON
02630      GO TO 9999
02640 90 WRITE(6,270)
02650 9999 CONTINUE
02660      WRITE(6,850)
02670      CTDP
02680 105 FORMAT(1H1,10X, 'THE NUMBER OF PROBLEMS TO BE SOLVED IS',
02690      2X,I3, ' ')
02700 820 FORMAT(5X,15,3F12,4,F10,1)
02710 830 FORMAT(///,5X, 'POSITION', 2X, 'DEFLECTION', 3X, 'MEASURED', 3X,
02720      8 'DIFFERENCE', 3X, '% DIFF. ')
02730 9000 FORMAT(///,3X, 'THE FINAL MODULUS VALUES ARE', ///,
02740      8 4(F10,0,4X))
02750 200 FORMAT(1H, 'A80)
02760 210 FORMAT(V)
02770 240 FORMAT(///,T30, 'IN THE A MATRIX', ///, T13, '1', T30, '2', T48, '3',
02780      8 T68, '4', //)
02790 251 FORMAT(2X,4(F10,0,3X))
02800 250 FORMAT(2X,4(E16,6,3X))
02810 260 FORMAT(///,T30, 'IN THE S MATRIX', ///, T13, '1', T30, '2', T48, '3',
02820      2 T68, '4', //)
02830 270 FORMAT(' THIS MATRIX HAS NO SOLUTION')
02840 290 FORMAT(///,T30, 'IN THE B MATRIX', ///, T13, '1', T30, '2', T48, '3',
02850      8 T68, '4', //)
02860 300 FORMAT(///,T30, 'IN THE C MATRIX', ///, T13, '1', T30, '2', T48, '3', T68, '4',
02870      2, //)
02880 310 FORMAT(125, 'THE MODULUS VALUES ARE NOT WITHIN TOLERANCE')
02890 1000 FORMAT(A80)
02900 600 FORMAT(5X, 'NUMBER OF VARIABLE LAYERS AND TARGET DEFLECTIONS = ',
02910      8 I2, ' ')
02920 619 FORMAT(1X,///,15X, 'DEFLECTION READINGS IN MILS', ///,
02930      2 ' POSITION NO:', 6X,4(9X,11,2X))
02940 620 FORMAT(' DEFLECTIONS:', 6X,4(F12,3))

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02950 621 FORMAT('WEIGHTING FACTOR: ',4,F12.3)
02960 650 FORMAT('5X, VARIABLE SYSTEM',9X,VALUE OF',12X,VALUE OF',,
02970 25X,LAYER NO',3X,LAYER NO',5X,MAXIMUM MODULUS',5X,MINIMUM MODUL
02980 20X,')
02990 660 FORMAT(9X,I2,9X,I2,10X,F10.1,10X,F10.1)
03000 710 FORMAT(5('),20X,'FOR EQUATION A + S + E = DEFLECTION',)
03010 720 FORMAT(5('),23X,'FOR THE EQUATION (B) + (E) = (C)',)
03020 761 FORMAT(80(1H),,5X,'DATA FOR DEVELOPING EQUATIONS FOR ITERATIONS',
03030 2' NO.',2X,I2)
03040 760 FORMAT(1H1,5('),5X,'DATA FOR DEVELOPING EQUATIONS FOR ITERATIONS',
03050 2' NO.',12X,5X,'LAYER INITIAL CHANGED OFFSET',10X,
03060 2'DEFLECTIONS',5X,'NO.',5X,'MODULUS MODULUS',5X,'DISC. INITIAL
03070 2' CHANGED READINGS',,72(')
03080 770 FORMAT(6X,I2,4X,F8.0,3X,F8.0,4X,F6.2,3X,F6.3,6X,F6.3,3X,F6.3)
03090 780 FORMAT(136,F6.2,3X,F6.3,6X,F6.3,3X,F6.3)
03100 790 FORMAT(')
03110 810 FORMAT(72(')
03120 715 FORMAT(28X,'AVERAGE:',2F10.4)
03130 840 FORMAT(23X,'ABSOLUTE SUM:',2F10.4,,22X,
03140 2'ARITHMETIC SUM:',10X,F10.4)
03150 850 FORMAT(1H,26H***** END OF PROGRAM *****
03160 1212 FORMAT(1H1,,,,,'PROBLEM NUMBER ',I4,/)
03170 END
03180 SUBROUTINE CHEVRON
03190C040 65P040 N-LAYER ELASTIC SYSTEMS PROGRAM
03200C CALCULATING STRESSES, STRAINS, AND DEFLECTIONS
03210C191MN ***** MAIN ROUTINE - N-LAYER ELASTIC SYSTEM *****
03220C
03230 COMMON /PMCDY/RR(10), Z2(10), E(5), V(5), MH(4),
03240 2 H(4), AZ(396), A(396,5), B(396,5), C(396,5),
03250 2 D(396,5), AJ(396), RJ1(396), RJ0(396), TITLE(20),
03260 2 TEST(11), BZ(100), X(5,4,4), SC(4), FM(2,2),
03270 2 PM(4,4,4),R, Z, AR, NS,
03280 2 N, L, ITN, RSZ, PSR,
03290 2 ROM, RMU, SF, CSZ, CST,
03300 2 CSR, CTR, CDM, CMU, PSI,
03310 2 NLINE, NOUTP, NTEST, I, ITN4,
03320 2 K, LC, JT, T2Z, PR,
03330 2 PA, P, EP, TIP, TIM,
03340 2 T1, T2, T3, T4, T5,
03350 2 T6, T2P, T2M, WA, BJ1,
03360 2 BJ0, ZF, SZ1, SZ2, SG1,
03370 2 SG2, PH, PH2, VKP2,
03380 2 VK4, VKP4, VKK8, RDT, RDS
03390 COMMON/DPT/COUNTR,DEF(4),NLAYS
03400 INTEGER COUNTR
03410 DATA ASTER, PERD/4H****, 4H.... /
03420 IF(COUNTR.EQ.99) GO TO 7
03430 IF(COUNTR.GE.2) GO TO 26
03440 CALL FLGE0F(41,NFILE)
03450C
03460C ** COMPUTE ZEROS OF J1(X) AND J0(X). SET UP GAUSS CONSTANTS **
03470 K = ITN+1
03480 DO 2 I=7,K,2
03490 T = 1/2
03500 TD = 4.0*T - 1.0
03510 2 BZ(I) = 3.1415927*(T - 0.25 + 0.050661/TD
03520 2 -0.053041*TD**3 + 0.262051*TD**5)
03530 DO 3 I=8,ITN,2
03540 T = (I-2)/2

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03550      TD = 4.0*T + 1.0
03560      3      RD(I) = 3.1415927*(T + 0.25 - 0.151982*TD
03570      3      + 0.015399 TD**3 - 0.245270*TD**5)
03580C
03590      10 READ(5, 398) TITLE
03600      398 FORMAT(20A4)
03610      IF(NFILE.EQ.1) GO TO 9999
03620      310 FORMAT(20A4)
03630      READ(5, 399) LINENU, WGT, PSI, NOUTP, NPUN
03640      311 FORMAT(2F12.0, I12, I1)
03650      READ(5, 399) LINENU, NS, (E(I), V(I), I = 1, NS)
03660      NLAYS = NS
03670      301 FORMAT(13.F9.0, 9F6.0)
03680      399 FORMAT(V)
03690      1 FORMAT(6X, 10F6.0)
03700      1001 CONTINUE
03710      N = NS - 1
03720      READ(5, 399) LINENU, (HH(I), I=1, N)
03730      313 FORMAT(10F6.0)
03740      7 READ(5, 399) LINENU, IR, (PR(I), I=1, IR)
03750      IF(IP.EQ.0) RETURN
03760      2001 CONTINUE
03770      READ(5, 399) LINENU, IZ, (ZZ(I), I=1, IZ)
03780      IF(COUNTP.EQ.99) GO TO 26
03790      3001 CONTINUE
03800      AP = 30PT (WGT/(3.14159*PSI))
03810      NLINE = 17*NS
03820      NPAGE = 1
03830      WRITE(6, 350) (TITLE(I), I=1, 20)
03840      350 FORMAT(1H1//1H0, 5H*****20A4)
03850      WRITE(6, 351)
03860      351 FORMAT(1H0, 23X, 26HTHE PROBLEMPARAMETERS ARE//)
03870      WRITE(6, 352) WGT, PSI, AP
03880      352 FORMAT(1H0, 5X, 12HTOTAL LOAD.., 8X, F10.2, 5H LBS, /
03890      8      1H0, 5X, 15HTIRE PRESSURE.., 5X, F10.2, 5H PSI, /
03900      8      1H0, 5X, 13HLOAD RADIUS.., 7X, F10.2, 5H IN.//)
03910      WRITE(6, 353)
03920      353 FORMAT(1H0, 5X, 9HLAYER NO., 8X, 7HMODULUS, 8X, 14HPOISSONS RATIO,
03930      2      8X, 9HTHICKNESS//)
03940      WRITE(6, 354) (I, E(I), V(I), HH(I), I=1, N)
03950      354 FORMAT(1H0, 8X, I3, 9X, F10.0, 11X, F5.3, 14X, F6.2)
03960      WRITE(6, 349) NS, E(NS), V(NS)
03970      349 FORMAT(1H0, 8X, I3, 9X, F10.0, 11X, F5.3, 11X, 14HSEMI-INFINITE ///)
03980      IF(COUNTP.NE.99) GO TO 27
03990      WRITE(6, 348)
04000      348 FORMAT(1H, 1X, 1HR, 3X, 1H2, 11X, 8HVERTICAL, 2X, 10HTANGENTIAL,
04010      8      3X, 6HRADIAL, 6X, 5HSHEAR, 6X, 4HBULK)
04020      27 CONTINUE
04030C      ** ADJUST LAYER DEPTHS **
04040      H(1)=HH(1)
04050      DO 25 I=2, N
04060      25 H(I)=H(I-1)+HH(I)
04070      CALL CHECK(1)
04080      26 CONTINUE
04090      IF(COUNTP.EQ.99) WRITE(6, 348)
04100      IPT=0
04110C      ** START ON A NEW P **
04120      100 IPT=IPT+1
04130      IF(IPT.IP) RETURN
04140      105 P=PP-IPT)

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04150      DO 31 I=1,I2
04160      DO 31 J=1,N
04170      TZ = ABS (H(J) - Z2(I))
04180      IF (TZ - .0001) 32,32,31
04190      32 Z2(I) = -H(J)
04200      31 CONTINUE
04210      IF (COUNTR.NE.99) GO TO 39
04220      WRITE(6, 355)
04230      NLINE = NLINE+1
04240      355 FORMAT(1H )
04250      39 CONTINUE
04260C    ** CALCULATE THE PARTITION **
04270      CALL PART
04280C    ** CALCULATE THE COEFFICIENTS **
04290      DO 125 I=1,ITN4
04300      P=A2(I)
04310      107 CONTINUE
04320      IF (NS.GT.5) GO TO 108
04330      CALL COE5(I)
04340      GO TO 109
04350      108 CONTINUE
04360      CALL CO15(I)
04370      109 IF (P) 115,115,110
04380      110 PP = P*P
04390      CALL BESSEL (0,PP,Y)
04400      PJ0(I) = Y
04410      CALL BESSEL (1,PP,Y)
04420      PJ1(I) = Y
04430      115 PA=P*PP
04440      CALL BESSEL (1,PA,Y)
04450      AJ(I)=Y
04460      CALL CHECK (2)
04470      125 CONTINUE
04480      195 IZT=0
04490C    ** START ON A NEW Z **
04500      200 IZT=IZT+1
04510      IF (IZT-IZ) 205,205,100
04520      205 Z=ABS (Z2(IZT))
04530      IF ( NLINE - 54 ) 207,206,206
04540      206 NPAGE = NPAGE + 1
04550      NLINE = 8
04560      207 CONTINUE
04570C    ** FIND THE LAYER CONTAINING Z **
04580      T2Z = 0.0
04590      DO 210 J1=1,N
04600      J=NS-J1
04610      IF (Z-H(J)) 210,215,215
04620      210 CONTINUE
04630      L = 1
04640      GO TO 34
04650      215 L=J+1
04660      IF (Z2(IZT)) 33,34,34
04670      33 L = J
04680      T2Z = 1.0
04690      34 CONTINUE
04700      CALL CALCIN(IRT)
04710      IF (T2Z) 36,36,35
04720      35 Z2(IZT) = -Z2(IZT)
04730      IZT = IZT-1
04740      36 CONTINUE

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```

04750      GO TO 200
04760 9999 CALL EXIT
04770      STOP
04780      END
04790      BLOCK DATA
04800
04810      COMMON /PMCDY/ RR(10), ZZ(10), E(5), V(5), HH(4),
04820      2      H(4), AZ(396), A(396,5), B(396,5), C(396,5),
04830      2      D(396,5), AJ(396), RJ1(396), RJ0(396), TITLE(20),
04840      2      TEST(11), BZ(100), X(5,4,4), SC(4), FM(2,2),
04850      2      PM(4,4,4), P, Z, AP, NS,
04860      2      N, L, ITN, RSZ, RSR,
04870      2      POM, PMU, SF, CSZ, CST,
04880      2      CSR, CTR, COM, CMU, PSI,
04890      2      NLINE, NOUTP, NTEST, I, ITN4,
04900      2      K, LC, JT, TZZ, PR,
04910      2      PA, P, EP, TIP, TIM,
04920      2      T1, T2, T3, T4, T5,
04930      2      T6, T2P, T2M, WA, BU1,
04940      2      BJ0, ZF, SZ1, SZ2, SG1,
04950      2      SG2, PH, PH2, VK2, VKP2,
04960      2      VK4, VKP4, VKK8, RDT, RDS
04970      DIMENSION ZB(6)
04980      EQUIVALENCE (BZ,ZB)
04990      DATA ZB/0.0,1.0,2.4048,3.8317,5.5201,7.0156/
05000      DATA ITN/46/, ITN4/184/
05010      END
05020      SUBROUTINE BESSEL(NI,XI,Y)
05030      *****SUBROUTINE BESSEL - N-LAYER ELASTIC SYSTEM *****
050400
05050      DIMENSION PZ(6),OZ(6),P1(6),Q1(6),D(20)
05060      DATA PZ/1.0E0,-1.125E-4,2.8710938E-7,-2.3449658E-9,
05070      23.9806841E-11,-1.1536133E-12/, OZ/-5.0E-3,4.6875E-6,
05080      2-2.3255859E-8, 2.8307087E-10, -6.3912096E-12, 2.3124704E-12/,
05090      2P1/ 1.0E0, 1.875E-4, -3.6914063E-7, 2.7713232E-9,
05100      2-4.5114421E-11,1.2750463E-12/, Q1/1.5E-2, -6.5625E-6,
05110      22.8423828E-8,-3.2662024E-10, 7.1431166E-12, -2.5327056E-13/,
05120      2PI/3.1415927/
051300
051400
05150      9 N = NI
05160      X = XI
05170      IF (X-7.0) 10,10,160
051800
05190      10 X2=X/2.0
05200      FAC=-X2*X2
05210      IF (N) 11,11,14
05220      11 C=1.0
05230      Y=C
05240      DO 13 I=1,34
05250      T=I
05260      C=FAC*C/(T*T)
05270      TEST=ABS (C) - 10.0**(-8)
05280      IF (TEST) 17,17,12
05290      12 Y=Y+C
05300      13 CONTINUE
05310      14 C=X2
05320      Y=C
05330      DO 16 I=1,34
05340      T=I

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05350      C=FAO*(C*(T*(T+1.0))
05360      TEST=ARI*(C) - 10.0**(-8)
05370      IF (TEST) 17,17,15
05380      15 V=Y+C
05390      16 CONTINUE
05400      17 RETURN
05410      180 IF (N) 161,161,164
05420C
05430C
05440      161 DO 162 I=1,6
05450          D(I) = PZ(I)
05460          D(I+10) = OZ(I)
05470      162 CONTINUE
05480          GO TO 163
05490C
05500      164 DO 165 I=1,6
05510          D(I) = PI(I)
05520          D(I+10) = OI(I)
05530      165 CONTINUE
05540      163 CONTINUE
05550          T1 = 25.0/X
05560          T2=T1*T1
05570          P = D(6)*T2+D(5)
05580          DO 170 I=1,4
05590              J = 5-I
05600              P = P+T2+D(J)
05610      170 CONTINUE
05620          Q = D(16)*T2+D(15)
05630          DO 171 I=1,4
05640              J = 5-I
05650              Q = Q+T2+D(J+10)
05660      171 CONTINUE
05670          Q = Q*T1
05680C
05690          T4 =DSQRT (X*PI)
05700          T6 = SIN (X)
05710          T7 = COS (X)
05720C
05730          IF (N) 180,180,185
05740C
05750      180 T5 = ((P-Q)*T6 + (P+Q)*T7)/T4
05760          GO TO 99
05770      185 T5 = ((P+Q)*T6 - (P-Q)*T7)/T4
05780      99 Y = T5
05790          RETURN
05800          END
05810          SUBROUTINE PART
05820C          *****SUBROUTINE PART - N-LAYER ELASTIC SYSTEM *****
05830C
05840          COMMON /RMCDY/RR(10), ZZ(10), E(5), V(5), HH(4),
05850      2          H(4), AZ(396), A(396,5), B(396,5), C(396,5),
05860      2          D(396,5), AJ(396), RJ1(396), RJ0(396), TITLE(20),
05870      2          TEST(11), BZ(100), X(5,4,4), SC(4), FM(2,2),
05880      2          PM(4,4,4), R, Z, AR, NS,
05890      2          N, L, ITN, RSZ, RSR,
05900      2          ROM, RMU, SF, CSZ, CST,
05910      2          CSR, CTR, CDM, CMU, PSI,
05920      2          NLINE, NOUTP, NTEST, I, ITN4,
05930      2          K, LC, JT, TZZ, PR,
05940      2          PA, P, EP, TIP, TIM.

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05950      T1,      T2,      T3,      T4,      T5,
05960      T6,      T2P,      T2M,      WA,      RJ1,
05970      BJ0,      CF,      C21,      C22,      C61,
05980      CG2,      PH,      PH2,      VK2,      VKP2,
05990      VK4,      VKP4,      VKP8,      PDT,      RDC
06000      DATA  G1 0.86113631, G2 0.33998104
06010      4 ZF = AP
06020      NTEST = 2
06030      IF (P) 8,8,9
06040      9 CONTINUE
06050      NTEST = AP/P + .0001
06060      IF (NTEST) 6,6,5
06070      6 CONTINUE
06080      NTEST = P/AP + .0001
06090      CF = P
06100      5 CONTINUE
06110      NTEST = NTEST + 1
06120      IF (NTEST-10) 8,8,7
06130      7 CONTINUE
06140      NTEST = 10
06150      8 CONTINUE
06160C      ** COMPUTE POINTS FOR LEGENDRE-GAUSS INTEGRATION **
06170      15 K = 1
06180      CALL CHECK (9)
06190      ZF = 2.0*ZF
06200      SZ2 = 0.0
06210      DO 28 I=1,ITN
06220          SZ1 = SZ2
06230          SZ2 = BZ(I+1)/ZF
06240          SF = SZ2 - SZ1
06250          PP = SZ2 + SZ1
06260          SG1=SF*G1
06270          SG2=SF*G2
06280          AZ(K)=PP-SG1
06290          AZ(K+1)=PP-SG2
06300          AZ(K+2)=PP+SG2
06310          AZ(K+3)=PP+SG1
06320          K = K + 4
06330      CALL CHECK (10)
06340      28 CONTINUE
06350      40 RETURN
06360      END
06370      SUBROUTINE CALCIN(IRT)
06380C      *****SUBROUTINE CALCIN - N-LAYER ELASTIC SYSTEM *****
06390C
06400      COMMON  /RMCDY/RR(10),  ZZ(10),  E(5),  V(5),  HH(4),
06410      H(4),  AZ(396),  A(396,5),  B(396,5),  C(396,5),
06420      D(396,5),  AJ(396),  RJ1(396),  RJ0(396),  TITLE(20),
06430      TEST(11),  BZ(100),  X(5,4,4),  SC(4),  FM(2,2),
06440      PM(4,4,4),  R,  Z,  AR,  NS,
06450      N,  L,  ITN,  RSZ,  PSR,
06460      PDM,  RMU,  SF,  CSZ,  CST,
06470      CSR,  CTR,  CDM,  CMU,  PSI,
06480      NLINE,  NOUTP,  NTEST,  I,  ITN4,
06490      K,  LC,  JT,  TZZ,  PR,
06500      PA,  P,  EP,  TIP,  TIM,
06510      T1,  T2,  T3,  T4,  T5,
06520      T6,  T2P,  T2M,  WA,  BJ1,
06530      BJ0,  CF,  C21,  C22,  C61,
06540      CG2,  PH,  PH2,  VK2,  VKP2,

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06550      *          VK4,      VKP4,      VKK8,      PDT,      PDC
06560      COMMON OPT COUNTER,DEF(4),NLAYS
06570      INTEGER COUNTER
06580      DIMENSION M(4)
06590      DATA M/0.34785485,2*0.65214515,0.34785485/
06600
06610      2 VL=2.0*V(L)
06620      EL=(1.0+V(L))/E(L)
06630      VL1=1.0-VL
06640      CSZ=0.0
06650      CST=0.0
06660      CSP=0.0
06670      CTR=0.0
06680      CDM=0.0
06690      CMU=0.0
06700      NTI1 = NTEST + 1
06710      ITC = 1
06720      JT = 0
06730      ARP = AR
06740      IF (NOUTP) 4,4,5
06750      4 ARP = ARP*PSI
06760      5 CONTINUE
06770      10 DO 40 I=1,ITN
06780      INITIALIZE THE SUB-INTEGRALS
06790      PSZ=0.0
06800      RST=0.0
06810      RSR=0.0
06820      PTR=0.0
06830      RDM=0.0
06840      PMU=0.0
06850      COMPUTE THE SUB-INTEGRALS
06860      K = 4*(I-1)
06870      DO 30 J=1,4
06880      J1 = K + J
06890      F=AZ(J1)
06900      EP=EXP(-P*Z)
06910      T1=B(J1,L)*EP
06920      T2=D(J1,L)/EP
06930      T1P=T1+T2
06940      T1M=T1-T2
06950      T1=(A(J1,L)+B(J1,L)*Z)*EP
06960      T2=(C(J1,L)+D(J1,L)*Z)/EP
06970      T2P=P*(T1+T2)
06980      T2M=P*(T1-T2)
06990      WA=AJ(J1)*W(J)
07000      CALL CHECK (3)
07010      IF (R) 20,20,15
07020      15 BJ1=PJ1(J1)*P
07030      BJ0=PJ0(J1)*P
07040      RSZ=PSZ+WA*P*BJ0*(VL1*T1P-T2M)
07050      RDM=RDM+WA*EL*BJ0*(2.0*VL1*T1M-T2P)
07060      RTR=RTR+WA*P*BJ1*(VL*T1M+T2P)
07070      PMU=PMU+WA*EL*BJ1*(T1P+T2M)
07080      RSR=RSR+WA*(P*BJ0*((1.0+VL)*T1P+T2M)-BJ1*(T1P+T2M)/R)
07090      RST=RST+WA*(VL*P*BJ0*T1P+BJ1*(T1P+T2M)/R)
07100      CALL CHECK (4)
07110      GO TO 30
07120      SPECIAL ROUTINE FOR R = ZERO
07130      20 PP=P*P
07140      RSZ=RSZ+WA*PP*(VL1*T1P-T2M)

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07150      PDM=PDM+MA*EL*P*(2.0*VL1*T1M-T2P)
07160      PCT=PCT+MA*PP*(VL+0.5*T1P+0.5*T2M)
07170      PPR=PCT
07180      CALL CHECK (5)
07190 30 CONTINUE
07200
07210      IF = (AZ(K+4) - AZ(K+1))/1.7222726
07220      CSZ=CSZ+RSZ*SF
07230      CST=CST+PST*SF
07240      CSR=CSR+PSR*SF
07250      CTP=CTP+PTR*SF
07260      COM=COM+PDM*SF
07270      CMU=CMU+PMU*SF
07280      RSZ = 2.0*RSZ+AP*SF
07290      CALL CHECK (6)
07300      TESTH = ABS (RSZ)-10.0**(-4)
07310      IF (ITS-NTS1) 31,32,32
07320 31 CONTINUE
07330      TEST(ITS) = TESTH
07340      ITS = ITS+1
07350      GO TO 40
07360 32 CONTINUE
07370      TEST(NTS1) = TESTH
07380      DO 33 J = 1,NTTEST
07390      IF (TESTH-TEST(J)) 35,36,36
07400 35 CONTINUE
07410      TESTH = TEST(J)
07420 36 CONTINUE
07430      TEST(J) = TEST(J+1)
07440 33 CONTINUE
07450      IF (TESTH) 50,50,40
07460 40 CONTINUE
07470      JT = 1
07480      CALL HIGHM
07490 50 CSZ=CSZ+APP
07500      CALL CHECK (7)
07510      CST=CST+APP
07520      CTP=CTP+APP
07530      CSR=CSR+APP
07540      COM=COM+APP
07550      IF (COUNTR.NE.99) DEF (IRT)=COM*1000.
07560      CMU=CMU+APP
07570      BSTS = CSZ+CST+CSR
07580      VCTR = (CSZ-V(L))* (CST+CSR)/E(L)
07590      BST = BSTS * (1.0-2.0*V(L))/E(L)
07600      IF (TZ) 72,72,71
07610 71 Z = -Z
07620 72 CONTINUE
07630      RDS=(CSR-V(L))* (CSZ+CST)/E(L)
07640      CST=2.0*(1.0+V(L))*CTR/E(L)
07650      PDT = (CCT - V(L) * (CSZ + CSR))/E(L)
07660      IF (COUNTR.NE.99) GO TO 99
07670      WRITE (6,315) P,Z,CSZ,CST,CSR,CTP,BSTS
07680      WRITE (6,318) VSTR,PDT,RDS,CST,BST
07690      WRITE (6,317) COM
07700 315 FORMAT (1H0,F4.1,F6.1,1X,5HSTRE ,1PSE11.3)
07710 318 FORMAT (1H ,11X,5HSTRA ,1PSE11.3)
07720 317 FORMAT (1H ,11X,5HDSPL ,1PE11.3)
07730      NLINE = NLINE + 3
07740      IF (JT) 99,99,60

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07750      60 WRITE(6,316)
07760      316 FORMAT ('H+127K,4HLOW')
07770      99 RETURN
07780      END
07790      SUBROUTINE HIGHM
07800+ *      *****SUBROUTINE HIGHM - N-LAYER ELASTIC SYSTEM *****
078100      DETAIL LIST
078200      LABEL
078300HIGHM *****SUBROUTINE HIGHM - N-LAYER ELASTIC SYSTEM *****
078400
07850      RETURN
07860      END
07870      SUBROUTINE CHECK(KIN)
078800+ *      *****SUBROUTINE CHECK - N-LAYER ELASTIC SYSTEM *****
078900
07900      COMMON /PMCOY/RR(10), ZZ(10), E(5), V(5), HH(4),
07910      %      H(4), AZ(396), A(396,5), B(396,5), C(396,5),
07920      %      D(396,5), AJ(396), RJ1(396), RJ0(396), TITLE(20),
07930      %      TEST(11), BZ(100), X(5,4,4), SC(4), FM(2,2),
07940      %      PM(4,4,4), R, Z, AR, NS,
07950      %      N, L, ITN, RSZ, RSR,
07960      %      RDM, RMU, SF, CSZ, CST,
07970      %      CSR, CTR, COM, CMU, PSI,
07980      %      NLINE, NOUTP, NTEST, I, ITN4,
07990      %      K, LC, JT, TZZ, PP,
08000      %      PA, P, EP, TIP, TIM,
08010      %      T1, T2, T3, T4, T5,
08020      %      T6, T2P, T2M, WA, BJ1,
08030      %      BJ0, ZF, SZ1, SZ2, SG1,
08040      %      SG2, PH, PH2, VK2, VKP2,
08050      %      VK4, VKP4, VKK8, RDT, RDS
08060      RETURN
08070      END
08080      SUBROUTINE CODE(KIN)
080900      USE FOR ALL PROBLEMS, UP TO MAX DIMENSION OF 15 LAYERS
081000      REPROGRAMMED 1 MAY 1980 BY L J PRINTER - EXCELLENT ACCURACY
081100      NOTE DOUBLE ENTRIES FOR COE5 & CO15 PREVIOUSLY USED
081200      *****SUBROUTINE CODEE - N-LAYER ELASTIC SYSTEM *****
081300
08140      COMMON /PMCOY/RR(10), ZZ(10), E(5), V(5), HH(4),
08150      %      H(4), AZ(396), A(396,5), B(396,5), C(396,5),
08160      %      D(396,5), AJ(396), RJ1(396), RJ0(396), TITLE(20),
08170      %      TEST(11), BZ(100), X(5,4,4), SC(4), FM(4),
08180      %      PM(4,4,4), R, Z, AR, NS,
08190      %      N, L, ITN, RSZ, RSR,
08200      %      RDM, RMU, SF, CSZ, CST,
08210      %      CSR, CTR, COM, CMU, PSI,
08220      %      NLINE, NOUTP, NTEST, I, ITN4,
08230      %      K, LC, JT, TZZ, PP,
08240      %      PA, P, EP, TIP, TIM,
08250      %      T1, T2, T3, T4, T5,
08260      %      T6, T2P, T2M, WA, BJ1,
08270      %      BJ0, ZF, SZ1, SZ2, SG1,
08280      %      SG2, PH, PH2, VK2, VKP2,
08290      %      VK4, VKP4, VKK8, RDT, RDS
08300      PERL=4 0(2,2)
08310      ENTRY COE3(KIN)
08320      ENTRY CO15(KIN)
08330      LC = KIN
083400 I=MX      SET UP MATRIX X =DI+MI+KI+K+MD

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083500      COMPUTE THE MATRICES X(K)
083600      1 DO 10 K=1,N
083700          T1=E(K)*(.0+V(K+1))-(E(K+1)*(.0+V(K)))
083800          TIM=T1-1.0
083900          PH=P*H(K)
084000          PH2=PH*2.0
084100          VK2=2.0*V(K)
084200          VKP2=2.0*V(K+1)
084300
084400          VKK8=8.0*V(K)*V(K+1)
084500          VKP4=2.0*VKP2
084600          VK4=2.0*VK2
084700          X(K,1,1)=VK4-3.0-T1
084800          X(K,2,1)=0.0
084900          X(K,3,1)=TIM*(PH2-VK4+1.0)
085000          X(K,4,1)=-2.0*TIM*P
085100
085200          T3=PH2*(VK2-1.0)
085300          T4=VKK8+1.0-3.0*VKP2
085400          T5=PH2*(VKP2-1.0)
085500          T6=VKK8+1.0-3.0*VK2
085600
085700          X(K,1,2)=(T3+T4-T1*(T5+T6))/P
085800          X(K,2,2)=T1*(VKP4-3.0)-1.0
085900          X(K,4,2)=TIM*(1.0-PH2-VKP4)
086000
086100          X(K,3,4)=(T3-T4-T1*(T5-T6))/P
086200
086300          T3=PH2*PH-VKK8+1.0
086400          T4=PH2*(VK2-VKP2)
086500
086600          X(K,1,4)=(T3+T4+VKP2-T1*(T3+T4+VK2))/P
086700          X(K,3,2)=(-T3+T4-VKP2+T1*(T3-T4+VK2))/P
086800
086900          X(K,1,3)=TIM*(1.0-PH2-VK4)
087000          X(K,2,3)=2.0*TIM*P
087100          X(K,3,3)=VK4-3.0-T1
087200          X(K,4,3)=0.0
087300
087400          X(K,2,4)=TIM*(PH2-VKP4+1.0)
087500          X(K,4,4)=T1*(VKP4-3.0)-1.0
087600          K = K
087700      10 CONTINUE
087800      COMPUTE THE PRODUCT MATRICES PM
087900      SC(N)=4.0*(V(N)-1.0)
088000      IF (N-2) 13,11,11
088100      11 DO 12 K1=2,N
088200          M=NS-K1
088300          SC(M)=SC(M+1)*4.0*(V(M)-1.0)
088400      12 CONTINUE
088500      13 CONTINUE
088600
088700      Q(1,1)=1.
088800      Q(2,2)=1.
088900      Q(1,2)=0.
089000      QQ = P*2.0*H(N)
089100      IF (QQ.LT.-88.) QQ=-88.
089200      IF (QQ-88.) 15,15,16
089300      15 CONTINUE
089400      Q(1,2)=EXP(-QQ)

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AD-A099 593

ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG--ETC F/G 13/2
NONDESTRUCTIVE TESTING FOR LIGHT AIRCRAFT PAVEMENTS. PHASE II.--ETC(U)
NOV 80 A J BUSH DOT-FA78WAI-848

UNCLASSIFIED

FAA-RD-80-9-2

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END

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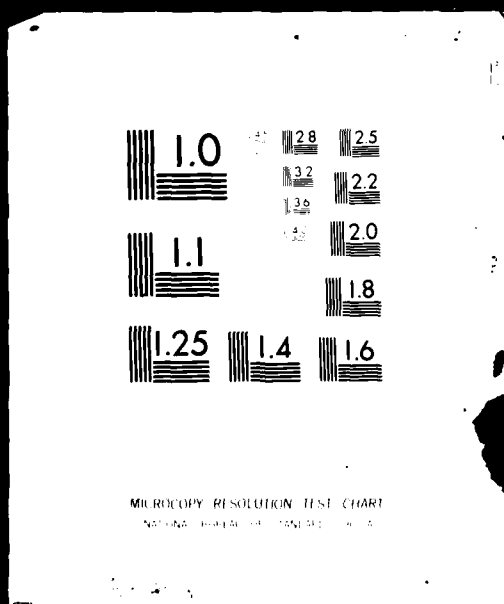
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2 OF 2

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099593



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089500      Q(2,1) IF NOT NEEDED FOR INITIALIZING THE PM MATRIX
08960      16 CONTINUE
089700      DO LOOP INITIALIZES PM(N,...
08980      DO 20 M=1,4
08990      LL=(M+1)/2
09000      DO 20 J=3,4
09010      PM(N,M,J)=X(N,M,J) * Q(LL,2)
09020      20 CONTINUE
09030      DO 26 K1=2,N
09040      K=N1-K1
09050      KK=K+1
09060      Q0 =P*2.*H(K)
09070      IF (Q0.LT.-88.) Q0=-88.
09080      IF (Q0-88.) 22,22,23
09090      22 CONTINUE
09100      Q(2,1)=EXP(Q0)
09110      Q(1,2)=1./Q(2,1)
09120      GO TO 24
09130      23 CONTINUE
09140      Q(1,2)=0.
09150      Q(2,1)=1.E20
09160      24 CONTINUE
09170      DO 25 M=1,4
09180      LL=(M+1)/2
09190      DO 25 J=3,4
09200      PM(K,M,J)=(X(K,M,1) * PM(KK,1,J)
09210      * X(K,M,2) * PM(KK,2,J) * Q(LL,1)
09220      * X(K,M,3) * PM(KK,3,J)
09230      * X(K,M,4) * PM(KK,4,J) * Q(LL,2)
09240      25 CONTINUE
09250      26 CONTINUE
092600      SOLVE FOR C(NS) AND D(NS)
09270
09280      T3=2.0*V(1)
09290      T4 =T3-1.0
09300
09310      FM(1)= P*(PM(1,1,3)+PM(1,3,3)) + T3*(PM(1,2,3)-PM(1,4,3))
09320      FM(2)= P*(PM(1,1,3)-PM(1,3,3)) + T4*(PM(1,2,3)+PM(1,4,3))
09330      FM(3)= P*(PM(1,1,4)+PM(1,3,4)) + T3*(PM(1,2,4)-PM(1,4,4))
09340      FM(4)= P*(PM(1,1,4)-PM(1,3,4)) + T4*(PM(1,2,4)+PM(1,4,4))
09350      DFAC=SC(1)/(FM(1)+FM(4)-FM(3)+FM(2))*P*P
09360      A(LC,NS) = 0.0
09370      B(LC,NS) = 0.0
09380      C(LC,NS) = -FM(3)*DFAC
09390      D(LC,NS) = FM(1)*DFAC
094000      BACKSOLVE FOR THE OTHER A,B,C,D
09410      DO 91 K1=1,N
09420      A(LC,K1)=(PM(K1,1,3)*C(LC,NS)+PM(K1,1,4)*D(LC,NS))/SC(K1)
09430      B(LC,K1)=(PM(K1,2,3)*C(LC,NS)+PM(K1,2,4)*D(LC,NS))/SC(K1)
09440      C(LC,K1)=(PM(K1,3,3)*C(LC,NS)+PM(K1,3,4)*D(LC,NS))/SC(K1)
09450      91 D(LC,K1)=(PM(K1,4,3)*C(LC,NS)+PM(K1,4,4)*D(LC,NS))/SC(K1)
09460      100 CONTINUE
09470      RETURN
09480      END
09490      SUBROUTINE SIMEQ (A,B,N,KERR,IDIM)
095000      SIMEQ
095100      THIS SUBROUTINE SOLVES A SYSTEM OF LINEAR EQUATIONS
095200      AX=B BY THE METHOD OF PIVOTAL CONDENSATION.IT IS USED
095300      FOR DENSE MATRICES OF COEFFICIENTS.
095400      CALLING ARGUMENTS:
095500      A: THE NAME OF AN N BY N MATRIX OF COEFFICIENTS OF THE EQUATIONS
095600      WHICH IS DESTROYED DURING COMPUTATION.

```

```

095700:      B: THE NAME OF AN ARRAY CONTAINING THE N CONSTANTS.
095800:      N: THE ORDER OF THE SYSTEM
095900:      KERR: INDICATOR RETURNED BY THE SUBROUTINE WHICH IS
096000:            ONE IF SYSTEM IS SINGULAR AND ZERO OTHERWISE.
096100:            READ A COLUMN BY COLUMN.
096200:
09630:      DIMENSION A*(DIM, DIM)*B*(DIM)*L*(50)*M*(50)
09640:      EPI=1E-6
09650:      EPSOR=EPI*EPI
09660:      KERR=0
096700:      CLEAR OUT PERMUTATION VECTORS
09680:      DO 3 I=1,N
09690:        M(I)=0
09700 3:      L(I)=0
097100:      LOOP FOR N PIVOT POINTS
09720:      DO 14 KP=1,N
09730:        P=0.
09740:        P10P=0.
09750:        DO 7 I=1,N
09760:          DO 7 J=1,N
09770:            IF (M(I)) 7,4,7
09780 4:            IF (L(J)) 7,5,7
09790 5:            T=A(I,J)
09800:            T10P=T*P
09810:            IF (T10P-P10P) 7,7,6
09820 6:            P=T
09830:            P10P=T10P
09840:            KP=I
09850:            KC=J
09860 7:            CONTINUE
09870:            IF (P10P-EPSOR) 17,17,8
09880 8:            M(KP)=KC
09890:            L(KC)=1
099000:      DIVIDE KEY ROW BY PIVOT
09910:      DO 30 J=1,N
09920:        IF (L(J)) 30,9,30
09930 9:        A(KP,J)=A(KP,J)/P
09940 30:      CONTINUE
09950:        BKR=B(KP)*P
09960:        B(KP)=BKR
099700:      SUBTRACT MULTIPLE OF KEY ROW FROM OTHER ROWS
09980:      DO 14 I=1,N
09990:        IF (I-KP) 31,14,31
10000 31:        P=A(I,KC)
10010:      DO 33 J=1,N
10020:        IF (L(J)) 33,32,33
10030 32:        A(I,J)=A(I,J)-P*A(KP,J)
10040 33:      CONTINUE
10050:        B(I)=B(I)-P*BKR
10060 14:      CONTINUE
100700:      REORDER RESULTS
10080:      DO 35 I=1,N
10090:        IP=M(I)
10100 35:        A(IP,1)=B(I)
10110:      DO 36 I=1,N
10120 36:        B(I)=A(I,1)
10130:      RETURN
101400:      ERROR ACTION
10150 17:      KERR=1
10160:      RETURN
10170:      END

```

READ:

•

APPENDIX C: GUIDE TO USE OF COMPUTER PROGRAM PAVEVAL

The computer program PAVEVAL calculates the allowable load-carrying capacity and the required overlay thickness for rigid and flexible pavements. A program listing is contained in the report by Weiss.³ Input guides, typical inputs, and typical outputs are furnished in this appendix for evaluation of load-carrying capability of both flexible and rigid pavements.

INPUT GUIDE FOR FLEXIBLE PAVEMENTS

Line 1

Title	80 characters
-------	---------------

Line 2

NSYS

NSYS = Number of problems to run

Line 3

EKEY

EKEY2

EKEY = Limiting strain and stress subroutine code: set = 2,
for calls to subroutine flex

EKEY2 = Pavement problem code: set = 0, for allowable load

Line 4

ES

EA

YRN

ALOAD

ALIN

CAREA

DSM

SWL

PCRATIO

ES = Subgrade modulus, psi

EA = Asphalt modulus of existing layer

YRN = Yearly load repetition number

ALOAD = Initial load, lb

ALIN = Load increment, lb

CAREA = Contact area (πr^2), in.²

DSM = Dynamic stiffness modulus, for reference only (any number)

SWL = Set = 0

PCRATIO = Pass-to-coverage ratio

Line 5

NLAYS	ISMO	IRED
-------	------	------

NLAYS = Number of layers in pavement system

ISMO = Request for rough computational procedure: set = 0

IRED = Input format for Line 6: set = 0

Line 6-1 through 6-(NLAYS-1) (one for each layer, except last layer)

E(i)	NU(i)	THICK(i)	AK(i)
------	-------	----------	-------

E(i) = Modulus of layer i

NU(i) = Poisson's ratio of layer i

THICK(i) = Thickness of layer i

AK(i) = Interface compliance: set all AK(i)'s = 0

Line 7

E(NLAYS)	NU(NLAYS)
----------	-----------

E(NLAYS) = Modulus of last layer

NU(NLAYS) = Poisson's ratio of last layer

Line 8

NLOAD

NLOAD = Number of loaded areas

Line 9 (one for each load)

LOSTRS(i)	RADIUS(i)	X(i)	Y(i)	HOSTR(i)	PSI(i)
-----------	-----------	------	------	----------	--------

LOSTRS(i) = Vertical load for load area i

RADIUS(i) = Radius of loaded area i

$X(i)$ = Abscissa of center of loaded area: set = 0
 $Y(i)$ = Ordinate of center of loaded area: set = 0
 $HOSTR(I)$ = Horizontal load for load area i: normally = 0
 $PSI(i)$ = Angle of $HOSTR(i)$ with respect to positive X-axis in
in degrees: normally = 0

Line 10

NPOS

NPOS = Number of depths that will be used for iteration purposes:
set = 2

Line 11-1 through 11-NPOS

LAYER(I)	AX(i)	AY(i)	DEPTH(i)	ETA(i)
----------	-------	-------	----------	--------

$LAYER(i)$ = Layer number for position i: set; $LAYER(1) = 1$, $LAYER(1)$
= NLAYS(last layer)

$AX(i)$ = Abscissa of position: set $AX(1) = AX(2) = 0$

$AY(i)$ = Ordinate of position: set $AY(1) = AY(2) = 0$

$DEPTH(i)$ = Depth from pavement surface to position: set; $DEPTH(1)$
= THICK(1), $DEPTH(2)$ = distance from pavement surface
to top of subgrade

$ETA(i)$ = Angle from which position is observed: set = 0

TYPICAL INPUT FOR FLEXIBLE PAVEMENT EVALUATION

01000H	
0200:IDENT:P01F300.BUSH	
0300:OPTION:FOPTAN	
0400:MIG3:060480/1700	
0500:USE:.6TLIT	
0600:FOPTY:XREF	
0700:SELECTA:PAVEVAL	
0800:NOTE:PAVEVAL	
0900:EXECUTE	
1000:LIMITS:30,30K.,15000	
110PTRF 1A 20 KIP SINGLE	LINE 1
120 1	LINE 2
130 2 0	LINE 3
140 8320 770000 25000 20000 1000 127 1000 0 7.94	LINE 4
150 3 0 0	LINE 5
160 770000 0.35 7.5 0	LINE 6-1
170 40304 0.35 20.5 0	LINE 6-2
180 8320 0.40	LINE 7
190 1	LINE 8
200 9500 6.36 0 0 0 0	LINE 9
210 2	LINE 10
220 1 0 0 7.5 0	LINE 11-1
230 3 0 0 22. 0	LINE 11-2
2400:ENDJOB	

TYPICAL OUTPUT FOR FLEXIBLE PAVEMENT EVALUATION

***** FLEXIBLE PAVEMENT ALLOWABLE LOAD *****

 STRL(SUBGRADE LIMITING STRAIN) = 0.00085465
 STRL2(ASPHALT LIMITING STRAIN) = 0.00027464
 ALOAD = 20000.
 ALIM = 1000.

SYSTEM NUMBER 1

LAYER NUMBER	CALCULATION METHOD	YOUNG'S MODULUS	POISSON'S RATIO	THICKNESS	INTERFACE SPRING COEFF
1	ROUGH	0.7700E 06	0.3500E 00	0.7500E 01	0.
2	ROUGH	0.4030E 05	0.3500E 00	0.2050E 02	0.
3		0.9320E 04	0.4000E 00		

LOAD NUMBER	NORMAL STRESS	SHEAR STRESS	RADIUS OF LOADED AREA	LOAD - POSITION X	LOAD - POSITION Y	SHEAR DIRECTION
1	0.1574E 03	0.	0.6360E 01	0.	0.	0.

POSITION NUMBER 1

LAYER NUMBER 1

COORDINATES

X 0. Y 0. Z 0.7500E 01
 DISTANCE TO LOAD-AXIS(1)
 0.

THETA 0.

DISPLACEMENTS

RADIAL 0.

TANGENTIAL 0.

VERTICAL 0:299MEP01

STRESSES RADIAL 0.2458E 03

TANGENTIAL 0.2458E 03

VERTICAL -0:2807E 02

RAD./TANG. 0.

RAD./VERT. 0.

TANG./VERT. 0.

STRAINS RADIAL 0.2193E-03

TANGENTIAL 0.2193E-03

VERTICAL -0:2871E-03

RAD./TANG. 0.

RAD./VERT. 0.

TANG./VERT. 0.

MAXIMUM NORMAL STRAIN = 0.00021928

7.50

POSITION NUMBER 2

LAYER NUMBER 3

COORDINATES

X 0. Y 0. Z 0.2000E 02
 DISTANCE TO LOAD-AXIS(1)
 0.

THETA 0.

DISPLACEMENTS

RADIAL 0.

TANGENTIAL 0.

VERTICAL 0:2133E-01

STRESSES RADIAL 0.7656E-01

TANGENTIAL 0.7656E-01

VERTICAL -0:3307E 01

RAD./TANG. 0.

RAD./VERT. 0.

TANG./VERT. 0.

STRAINS RADIAL 0.1674E-03

TANGENTIAL 0.1674E-03

VERTICAL -0:4120E-05

RAD./TANG. 0.

RAD./VERT. 0.

TANG./VERT. 0.

VERTICAL STRAIN = -0.00041205

20.00

POSITION NUMBER 1

LAYER NUMBER 1

COORDINATES

X 0. Y 0. Z 0.7500E 01

DISTANCE TO LOAD-AXIS(1)
0.
THETA 0.

DISPLACEMENTS

RADIAL
0.
TANGENTIAL
0.

STRESSES
RADIAL
0.2583E 03
TANGENTIAL
0.2583E 03

STRAINS
RADIAL
0.2504E 03
TANGENTIAL
0.2504E 03
MAXIMUM NORMAL STRAIN = 0.00023039

VERTICAL
0.2030E 01

VERTICAL
-0.2718E 02

VERTICAL
-0.2701E 03

RAD./TANG.
0.

RAD./TANG.
0.

7.50

TANG./VERT.
0.

TANG./VERT.
0.

RAD./VERT.
0.

RAD./VERT.
0.

POSITION NUMBER 2

LAYER NUMBER 3

COORDINATES

X 0. Y 0. Z 0.2000E 02

DISTANCE TO LOAD-AXIS(1)
0.
THETA 0.

DISPLACEMENTS

RADIAL
0.
TANGENTIAL
0.

STRESSES
RADIAL
0.8043E 01
TANGENTIAL
0.8043E 01

STRAINS
RADIAL
0.1759E 03
TANGENTIAL
0.1759E 03
VERTICAL STRAIN = -0.00043291

VERTICAL
0.2041E 01

VERTICAL
-0.3337E 01

VERTICAL
-0.4329E 03

RAD./TANG.
0.

RAD./TANG.
0.

20.00

TANG./VERT.
0.

TANG./VERT.
0.

RAD./VERT.
0.

RAD./VERT.
0.

POSITION NUMBER 1

LAYER NUMBER 1

COORDINATES

0. X 0. Y 8.750E 01
 DISTANCE TO LOAD-AXIS(1)
 0. THETA
 0.

DISPLACEMENTS

RADIAL
 0.
 STRESSES
 RADIAL
 0.270E 03
 STRAINS
 RADIAL
 0.2414E 03
 TANGENTIAL
 0.2414E-03
 0.00024136
 MAXIMUM POPRAL STRAIN =
 0.00024136
 VERTICAL
 0.3078E 01
 TANGENTIAL
 0.270E 03
 TANGENTIAL
 0.270E 03
 TANGENTIAL
 0.2414E 03
 0.00024136
 HAD./TANG.
 0.
 HAD./TANG.
 0.
 HAD./TANG.
 0.
 7.50
 TANG./VERT.
 0.
 TANG./VERT.
 0.
 TANG./VERT.
 0.
 TANG./VERT.
 0.

POSITION NUMBER 2

LAYER NUMBER 3

COORDINATES

0. X 0. Y 8.200E 02
 DISTANCE TO LOAD-AXIS(1)
 0. THETA
 0.

DISPLACEMENTS

RADIAL
 0.
 STRESSES
 RADIAL
 0.8426E 01
 STRAINS
 RADIAL
 0.1842E 03
 TANGENTIAL
 0.1842E-03
 -0.00045352
 VERTICAL STRAIN =
 -0.00045352
 VERTICAL
 0.2347E 01
 TANGENTIAL
 0.8426E-01
 TANGENTIAL
 0.8426E-01
 TANGENTIAL
 0.1842E 03
 0.1842E-03
 -0.00045352
 HAD./TANG.
 0.
 HAD./TANG.
 0.
 HAD./TANG.
 0.
 28.00
 TANG./VERT.
 0.
 TANG./VERT.
 0.
 TANG./VERT.
 0.
 TANG./VERT.
 0.

POSITION NUMBER 1

LAYER NUMBER 1

COORDINATES

0. X 0. Y 0.7500E 01
 DISTANCE TO LOAD-AXIS(1)
 0.

DISPLACEMENTS

RADIAL

0.

STRESSES

RADIAL

0.2829E 03

STRAINS

RADIAL

0.2523E-03

MAXIMUM NORMAL STRAIN = 0.00025233

TANGENTIAL

0.

TANGENTIAL

0.2829E 03

TANGENTIAL

0.2523E-03

VERTICAL

0.3815E-01

VERTICAL

-0.2878E 02

VERTICAL

-0.2858E-03

HAD./TANG.

0.

HAD./TANG.

0.

RAD./VERT.

0.

RAD./VERT.

0.

TANG./VERT.

0.

TANG./VERT.

0.

THETA
0.

7.50

POSITION NUMBER 2

LAYER NUMBER 3

COORDINATES

0. X 0. Y 0.2800E 02
 DISTANCE TO LOAD-AXIS(1)
 0.

DISPLACEMENTS

RADIAL

0.

STRESSES

RADIAL

0.8809E-01

STRAINS

RADIAL

0.1926E-03

VERTICAL STRAIN = -0.00047414

TANGENTIAL

0.

TANGENTIAL

0.8810E-01

TANGENTIAL

0.1926E-03

VERTICAL

0.2854E-01

VERTICAL

-0.3874E 01

VERTICAL

-0.4741E-03

HAD./TANG.

0.

HAD./TANG.

0.

RAD./VERT.

0.

RAD./VERT.

0.

TANG./VERT.

0.

TANG./VERT.

0.

THETA
0.

28.00

POSITION NUMBER 1
LAYER NUMBER 1
COORDINATES

	X	Y	Z	THETA
DISTANCE TO LOAD-AXIS(1)	0.	0.	0.750E 01	0.
TANGENTIAL				
0.				
VERTICAL				
0.3355E+01				
STRESSES				
RADIAL				
0.2952E 03				
TANGENTIAL				
0.2952E 03				
STRAINS				
RADIAL				
0.2633E+03				
MAXIMUM LONAL STRAIN =				
0.00626330				
VERTICAL				
0.3387E+03				
0.				
RAD./TANG.				
0.				
RAD./TANG.				
0.				
0.				
7.50				

C-9

POSITION NUMBER 2
LAYER NUMBER 3
COORDINATES

	X	Y	Z	THETA
DISTANCE TO LOAD-AXIS(1)	0.	0.	0.200E 02	0.
TANGENTIAL				
0.				
VERTICAL				
0.2861E+01				
STRESSES				
RADIAL				
0.9193E+01				
TANGENTIAL				
0.9193E+01				
STRAINS				
RADIAL				
0.2010E+03				
VERTICAL STRAIN =				
-0.00049475				
VERTICAL				
-0.4948E+03				
0.				
0.				
20.00				
RAD./TANG.				
0.				
RAD./TANG.				
0.				
0.				
0.				

POSITION NUMBER 1

LAYER NUMBER 1

COORDINATES

X 0. Y 0. Z 0.7500E 01

DISTANCE TO LOAD=AXIS(1)
0.

THETA
0.

DISPLACEMENTS

RADIAL

0.

STRESSES

RADIAL

0.3076E 03

STRAINS

RADIAL

0.2743E 03

MAXIMUM NORMAL STRAIN =

0.00027427

TANGENTIAL

0.

TANGENTIAL

0.3076E 03

TANGENTIAL

0.2743E 03

VERTICAL

0.3495E 01

VERTICAL

-0.3235E 02

VERTICAL

-0.3215E 05

0.

RAD./TANG.

0.

RAD./TANG.

0.

7.50

TANG./VERT.

0.

TANG./VERT.

0.

POSITION NUMBER 2

LAYER NUMBER 3

COORDINATES

X 0. Y 0. Z 0.2800E 02

DISTANCE TO LOAD=AXIS(1)
0.

THETA
0.

DISPLACEMENTS

RADIAL

0.

STRESSES

RADIAL

0.9576E 01

STRAINS

RADIAL

0.2094E 03

VERTICAL STRAIN =

-0.00051537

TANGENTIAL

0.

TANGENTIAL

0.9576E 01

TANGENTIAL

0.2094E 03

VERTICAL

0.2667E 01

VERTICAL

-0.4211E 01

VERTICAL

-0.35154E 03

0.

RAD./TANG.

0.

RAD./TANG.

0.

20.00

TANG./VERT.

0.

TANG./VERT.

0.

POSITION NUMBER 1

LAYER NUMBER 1

COORDINATES

0: 1
x 2
B. 750E 01
2

THEY
O.

DISTANCE TO LOAD (M) (1)

**DISPLACEMENTS
RADIAL**

SPLASH RADIAL

TANGENTIAL

VERICAL
003435003

SYNTHESIS
RADIAL
0:390E 03

0:3198E 03

0.3198E 0

05471A 02
030500Z

SYNOPSIS

SYNOPSIS

TANGENTIAL

742185A

0.2832E+03	0.2852E+03
MAXIMUM NORMAL STRAIN =	0.00920524

9.

7:30

AD, VERY.

YANGS/MERT.

BAD: IVER.

TANGEN, MERT

ALREADY 3 20500.

PSI 9 204:72

0320. XS - 8.

0:091345

```
.....d..ABCC1 = 0.00020504
SYN12 : 0.00009444.....
```

TOTAL ALLOWABLE MESH: 9.233"

THICK ARRAY - 20-55

7 50

44 - 2 THICK - 20 80

SUBJECTIVE PAGE - 1300

6

10

2.0.

202

6

C-114

74

[illegible]

POSITION NUMBER 4
LAYER NUMBER 2
COORDINATES

X 0. Y 0. Z 0.2800E 02

DISTANCE TO LOAD-ARIS(1)
0. THETA 0.

DISPLACEMENTS
RADIAL
TANGENTIAL
0.
STRESS
RADIAL
TANGENTIAL
STRAINS
RADIAL
TANGENTIAL

VERTICAL
0.2774E-01
VERTICAL
-0.4300E 01
VERTICAL
-0.3022E-08

RAD./TANG.
0.
RAD./TANG.
0.
RAD./VERT.
0.
RAD./VERT.
0.

TANG./VERT.
0.
TANG./VERT.
0.

TOTAL STRESS
TOTAL STRAIN
TOTAL DISPLACEMENT
XX 0.111E 02
YY 0.111E 02
ZZ 0.430E 01
XY 0.
XZ 0.
YZ 0.
UX 0.
UY 0.
UZ 0.277E-01

PRINCIPAL VALUES AND DIRECTIONS OF TOTAL STRESSES AND STRAINS
NORMAL STRESS
MAXIMUM 1.111E 02
MINIMUM 1.111E 02
TANGENTIAL STRESS
MAXIMUM 1.330E 01
MINIMUM 1.330E 01
SHEAR STRESS
MAXIMUM 0.775E 01
MINIMUM 0.
SHEAR STRAIN
MAXIMUM 0.260E-03
MINIMUM 0.260E-03
COMPONENT
X 1.000
Y 1.000
Z 0.
COMPONENT
X 0.707
Y 0.707
Z 0.
COMPONENT
X 0.707
Y 0.707
Z 0.

STRAIN ENERGY OF DISTORTION 0.2690E-02
STRAIN ENERGY 0.3080E-02

INPUT GUIDE FOR RIGID PAVEMENTS

Line 1

Title	80 Characters
-------	---------------

Line 2

NYSYS

NYSYS = number of problems to run

Line 3

EKEY	EKEY2
------	-------

EKEY = Limiting strain and stress subroutine code: set = 3, for calls to subroutine RPAL

EKEY2 = Pavement problem code: set = 0, for allowable load

Line 4

DSM	FAC	YRN	R	ALOAD	ALIN	CAREA	SWL
-----	-----	-----	---	-------	------	-------	-----

DSM = Dynamic stiffness modulus, for reference

FAC = Pass-to-coverage ratio

YRN = Yearly load repetition number

R = Flexural strength, psi

ALOAD = Initial load, lb

ALIN = Load increment, lb

CAREA = Contact area (πr^2), in.²

SWL = : set = 0

Line 5

NLAYS	ISMO	IREL
-------	------	------

NLAYS = Number of layers in pavement system

ISMO = Request for smooth computational procedure: set = 1

IREL = Input format for Line 6: set = 1

Line 6-1 through 6-(NLAYS-1) (one for each layer, except last layer)

E(i)	NU(i)	THICK(i)	ALK(i)
------	-------	----------	--------

E(i) = Modulus of layer i

NU(i) = Poisson's ratio of layer i

THICK(i) = Thickness of layer i

ALK(i) = Reduced interface compliance: set; ALK(1) = 1000, all
other ALK(i)'s = 0

Line 7

E(NLAYS)	NU(NLAYS)
----------	-----------

E(NLAYS) = Modulus of last layer

NU(NLAYS) = Poisson's ratio of last layer

Line 8

NLOAD

NLOAD = Number of loaded areas

Line 9 (one for each load)

LOSTRS(i)	RADIUS(i)	X(i)	Y(i)	HOSTR(i)	PSI(i)
-----------	-----------	------	------	----------	--------

LOSTRS(i) = Vertical load for load area i

RADIUS(i) = Radius of loaded area i

X(i) = Abscissa of center of loaded area: set = 0

HOSTR(i) = Horizontal load for load area i: normally = 0

PSI(i) = Angle of Hostr(i) with respect to positive x-axis in
degrees: normally = 0

Line 10

NPOS

NPOS = Number of depths that will be used for iteration purposes:
set = 1

Line 11-1 through 11-NPOS

LAYER(i)	AX(i)	AY(i)	DEPTH(i)	ETA(i)
----------	-------	-------	----------	--------

LAYER(1) = Layer number for position i; set = 1

AX(1) = Abscissa of position: set = 0

AY(1) = Ordinate of position: set = 0

DEPTH(1) = Depth from pavement surface to position; set = THICK(1)

ETA(1) = Angle from which position is observed: set = 0

TYPICAL INPUT FOR RIGID PAVEMENT EVALUATION

```

01000N
0201:IDENT:ROSF300.8UEN
0301:OPTION:FORTRAN
0401:M363:060480/1700
0501:USE:.GTUIT
0601:FORTY:VEEF
0701:SELECTA:PAVEVAL
0801:NOTE:PAVEVAL
0901:EXECUTE
1001:LIMITS:30,30K.,15000
110PCC FORD SECTION 8
120 1
130 3 0
140 1000 7.94 25000 799 15000 1000 127 0
150 3 1 1
160 4000000 0.15 6 1000
170 78787 0.30 10 0
180 12278 0.40
190 1
200 9500 6.36 0 0 0 0
210 1
220 1 0 0 6 0
2301:ENDJOB

```

LINE 1
 LINE 2
 LINE 3
 LINE 4
 LINE 5
 LINE 6-1
 LINE 6-2
 LINE 7
 LINE 8
 LINE 9
 LINE 10
 LINE 11-1

READY

TYPICAL OUTPUT FOR RIGID PAVEMENT EVALUATION

*** ROAD SECTION ***

A = 0.585610

I = 0.354860

YRP = 25000.

IAC = 7.9400

ICV = 52972.

*** RIGID PAVEMENT SELECT ALLOCABLE LOAD ***

PS = 759.

IS = 1000.

ALCAL = 15000.

ALCL = 1000.

ATPL = 748.59537145

POSITION NUMBER 1

LAYER NUMBER 1

COORDINATES

X 0. Y 0. Z 0.000E 01

THETA 0.

DISTANCE TO LOAD-AXIS(1) 0.

DISPLACEMENTS

RADIAL 0.

TANGENTIAL 0.

VERTICAL 0.1537E+04

STRESSIS

RADIAL 0.333E 03

TANGENTIAL 0.3630E 03

VERTICAL -0.1170E 02

STRATIS

RADIAL 0.7758E+04

TANGENTIAL 0.7758E+04

VERTICAL -0.3815E+04

RAD./TANG. 0.

RAD./VERT. 0.

TANG./VERT. 0.

MAXIMUM NORMAL STRESS = 362.5958E520

RAD./TANG. 0.

RAD./VERT. 0.

TANG./VERT. 0.

6.00

SYSTEM NUMBER 1

LAYER NUMBER 1

CALCULATION METHOD

YOUNG'S MODULUS 0.400E 07

POISSON'S RATIO 0.150E 00

THICKNESS 0.000E 01

REDUCED SPRING COMPL 0.100E 04

ENROUTE 0.7879E 05

SPECTR 0.1220E 05

0.300E 00

0.400E 00

LOAD NUMBER 1

NORMAL STRESS 0.110E 03

SHEAR STRESS 0.

RADIUS OF LOADED AREA 0.636E 01

LOAD - POSITION X 0. Y 0.

SHEAR DIRECTION 0.

ALQAD 7 1500,

PSI 154 01

53 . 562

1500 - 1900.

RST5 • 352:99581228

575L 3 340:59037145

TOTAL AVAILABLE HEIGHT = 31579

THICK AREA = 10.00

THICK = 6.03

2 TICK = 10.00

SECRET 11-5-65 11-5-65

6.00

2 0 2 6:9

3 0. 0. 36.00

14:00

PCB LAYER NUMBER 1

LAYER NUMBER 1

COORDINATES

X Y Z
0. 0. 0.

DISTANCE TO LOAD AXIS (Z) 0. THETA 0.

DISPLACEMENTS
RADIAL
0.
STRESSES
RADIAL
-0.3945E-03
TANGENTIAL
-0.7949E-04

TANGENTIAL
0.
TANGENTIAL
-0.3945E-03
TANGENTIAL
-0.7949E-04

VERTICAL
0.1847E+01
VERTICAL
-0.1180E-03
VERTICAL
0.1879E+00

RAD./TANG.
0.
RAD./TANG.
0.
RAD./TANG.
0.

RAD./VERT.
0.
RAD./VERT.
0.
RAD./VERT.
0.

0.00

TOTAL STRAINS 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03
TOTAL STRAINS 0.395E-04 0.395E-04 0.395E-04 0.395E-04 0.395E-04 0.395E-04
TOTAL STRAINS 0.395E-04 0.395E-04 0.395E-04 0.395E-04 0.395E-04 0.395E-04

PRINCIPAL VALUES AND DIRECTIONS OF TOTAL STRESSES AND STRAINS
NORMAL
MAXIMUM 0.118E-03 0.118E-03 0.118E-03 0.118E-03 0.118E-03 0.118E-03
MINIMUM 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03
MAXIMUM 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03
MINIMUM 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03
MAXIMUM 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03
MINIMUM 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03 0.395E-03

STRAIN ENERGY 0.395E-01
STRAIN ENERGY OF DISTORTION 0.395E-02

SECTION NUMBER 2

LAYER NUMBER 1

COORDINATES

0. X E. Y Z
0.000E 01

DISTANCE TO LOAD-AXIS (1)
C.

THETA
0.

DISPLACEMENTS

	TANGENTIAL	VERTICAL
0. RADIAL	0.	0.1839E-01
STRESSFS		
0. RADIAL	TANGENTIAL	RAD./TANG.
0.3630E 03	0.3630E 03	0.
STRAINS		
0. RADIAL	TANGENTIAL	RAD./TANG.
0.7758E-04	0.7758E-04	0.

	XX	YY	ZZ	XY	XZ	YZ	UX	UY	UZ
TOTAL STIFF	0.363E 03	0.363E 03	0.363E 03	0.	0.	0.	0.	0.	0.
TOTAL STIFF	0.776E-04	0.776E-04	0.776E-04	0.	0.	0.	0.	0.	0.154E-01
TOTAL STIFF	C E N T R I F U G A L								

PRINCIPAL VALUES AND DIRECTIONS OF TOTAL STRESSES AND STRAINS

	NORMAL STRESS	SHEAR STRESS	NORMAL STRAIN	SHEAR STRAIN	COMPONENT	COMPONENT	COMPONENT
MAXIMUM	3.263E 03	0.107E 03	0.776E-04	0.539E-04	1.000	0.	0.
MINIMUM	3.263E 03	0.107E 03	0.776E-04	0.539E-04	0.	0.	0.
MINIMUM	-3.117E 02	0.107E 03	-0.301E-04	0.539E-04	0.	0.	0.
MINIMUM	3.176E 02	0.107E 03	0.776E-04	0.539E-04	0.	0.	0.
MINIMUM	3.176E 03	0.107E 03	0.776E-04	0.539E-04	0.	0.	0.
MINIMUM	3.263E 03	0.107E 03	0.776E-04	0.539E-04	0.	0.	0.

STRAIN ENERGY C.2834E-01
STRAIN ENERGY OF DISTORTION 0.1345E-01

0-25

POSITION NUMBER 5

LAYER NUMBER 3

COORDINATES

0. 0. 0. 0.1050E 02

DISTANCE TO LOAD-ORIGIN 11
0.

THETA
0.

DISPLACEMENTS

	TANGENTIAL	VERTICAL	RAD./TANG.	RAD./VERT.	TANG./VERT.
0.	0.	0.0222E 02			
STRESSES					
RADIAL	TANGENTIAL	VERTICAL	RAD./TANG.	RAD./VERT.	TANG./VERT.
-0.617E 00	-0.617E 00	-0.433E 01	0.	0.	0.
STRAINS					
RADIAL	TANGENTIAL	VERTICAL	RAD./TANG.	RAD./VERT.	TANG./VERT.
0.1040E 03	0.1040E 03	-0.0000E 00	0.	0.	0.
0.010E 00	0.010E 00	0.010E 00	0.010E 00	0.010E 00	0.010E 00
0.010E 00	0.010E 00	0.010E 00	0.010E 00	0.010E 00	0.010E 00
0.010E 00	0.010E 00	0.010E 00	0.010E 00	0.010E 00	0.010E 00

PRINCIPAL VALUES AND DIRECTIONS OF TOTAL STRESSES AND STRAINS

	NORMAL STRESS	MAX. SHEAR STRESS	MIN. SHEAR STRESS	MAX. STRAIN	MIN. STRAIN	COMPONENT	COMPONENT
MAXIMUM	-0.61E 00	0.103E 03	0.103E 03	0.201E-03	0.201E-03	0.000	0.000
MINIMUM	-0.61E 00	0.103E 03	0.103E 03	0.201E-03	0.201E-03	0.000	0.000
MAXIMUM	-0.61E 01	-0.297E 03	0.127E 01	0.201E-03	0.201E-03	0.000	0.000
MINIMUM	-0.230E 01	0.127E 01	0.127E 01	0.201E-03	0.201E-03	0.000	0.000
MAXIMUM	0.230E 01	0.127E 01	0.127E 01	0.201E-03	0.201E-03	0.000	0.000
MINIMUM	0.230E 01	0.127E 01	0.127E 01	0.201E-03	0.201E-03	0.000	0.000
MAXIMUM	0.61E 00	0.103E 03	0.103E 03	0.201E-03	0.201E-03	0.000	0.000

STRAIN ENERGY 0.19400E 03
STRAIN ENERGY OF DISTORTION 0.4294E-03

DATA
FILM

6

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